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Hydrogen nitrogening in great discharge with AC power

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Abstract

The paper substantiates and experimentally shows the possibility of anhydrous nitriding in a glow discharge (BATR) with AC power supply (AC), as well as the possibility of switching the shape of pulses, changing their polarity, which is solved by introducing a glow discharge nitriding device with a power source alternating current of a given frequency. The analysis of the results of metallographic studies of the modified layer indicated the presence of a more uniform gradient of hardness in depth (gradient decreased by 1.7 - 3.5 times), which increases the wear resistance of parts and quality indicators of strengthening parts while reducing processing costs and installation costs. At BATR in CCR with supply of current of industrial frequency the installation for realization of process becomes cheaper. The latter factor will contribute, among other aspects, to the wider introduction of BATR technologies. The use of alternating current affects the course and results of nitriding, as periodic changes in the polarity of the electrodes of the chamber contributes to the cleaning of the surface from the adsorption layer, which positively affects the nature of nitrogen saturation (gradient of microhardness times), contributes to a significant change in the phase composition of the surface modified layer and allows to expand the technological capabilities of nitriding in the direction of obtaining the required performance characteristics of working surfaces, in particular tribological characteristics

Key words: nitriding, alternating current, cyclic-switched discharge

Substantiation of hydrogen nitrogenation in a glow discharge with ac power

To date, research continues on the theoretical foundations, improvement of technologies and structures and types of equipment for technological processes of anhydrous nitriding in the glow discharge (BATR) [1]. Widespread use of BATR in industry has led to the exclusion of ammonia from gaseous media and, thus, to a fundamental improvement in the working conditions of equipment and maintenance personnel, environmental friendliness of the process [2]. In turn, this has led to an expansion of the range of performance indicators in accordance with the requirements and conditions of the friction contact load [3, 4]. Much of the research is devoted to methods of providing discharge in fundamentally different hardware implementations of power supplies [4]. In addition to nitriding with a constant power supply from a DC source, installations with additional heating from special screens or thermoradiation heaters are used, which reduces the relationship between electrical parameters of the technological mode and mode factors, especially temperature, because the energy factor is not only glow discharge. The development of new theoretical approaches is based primarily on the basic principles of gas discharge physics [5, 6]. The technological process has become multi-stage, in which it consists of macro- or microphases, which also significantly affects the results and productivity of the processing process. Fundamentally different nitriding results are achieved due to the introduction of cyclic-switched discharge (CCR), in which compared to the period of time sufficient to extinguish the transition from the glow discharge to the arc, the power supply to the camera electrodes is interrupted. In addition to simplifying control systems in CCR installations, the positioning of parts in the chamber is simplified, as the presence of gaps between parts and equipment for placing parts in the chamber no longer plays such a significant role. However, given the fact that the power supply to the electrodes of the chamber when using alternating current is not all the time, but in a much shorter period, the processing productivity decreases to about the same extent. Voltage and current emissions at the beginning and end of the power cycle are a problem, which can cause local damage to the treated surface [7]. The aim of the research is to analyze the possibilities and conditions for simplifying the design of nitriding installations in the glow discharge, as well as the possibility of using as a power supply electrodes discharge chamber cyclic-switched or alternating current industrial frequency (HF). The structure and functional purpose of the individual components (for example, a three-chamber installation) are shown in Fig. 1. In the installation, when the process is powered by direct current, the power supply must include the following components: voltage regulator (set the voltage at the input to the power supply system); step-up transformer (under the influence of the control signal from the voltage regulator changes the voltage up to values of about 1200 V - at the end of the surface cleaning phase by cathodic bombardment; rectifier that converts alternating current into conditionally constant output voltage includes ripples of greater or lesser magnitude compared to the rated voltage, ballast rheostat for redistribution of electric current at the input of the chamber. With cyclic-switched power supply, there are significant voltage emissions at the beginning and end of the pulse up to values that can cause local surface damage. In addition, perhaps the most important argument, the discharge control system is significantly complicated by the mandatory inclusion of control pulse generators operating at a frequency of 1 - 5 kHz, as well as CCR significantly reduces the productivity of the modification process [2, 4].

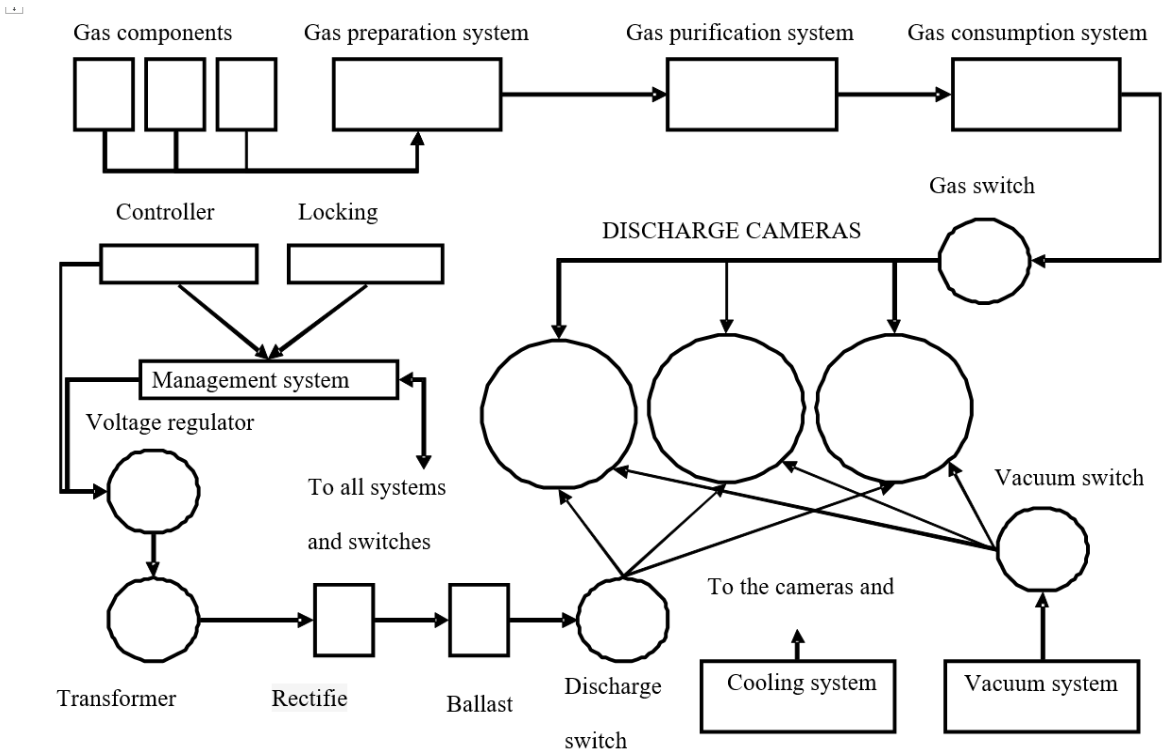

Fig. 1. Block diagram of a three-chamber installation

The above-described power structure of nitriding installations in the glow discharge is most suitable for single-phase processes, when the whole technological process takes place at constant technological parameters. However, it should be borne in mind that the main task of the power supply is not to maintain the specified electrical characteristics of the discharge, but to ensure a stable temperature on the surface of machined parts, which primarily affects the formation of a given phase-structural composition of the surface. Prospects for the practical application of anhydrous nitriding in a glow discharge with AC power supply (BATR HRT) are determined taking into account this circumstance as a determinant, because with variable current amplitude, respectively, in the period when the camera electrodes are negative voltage is no longer heated the cathode, which serves as a cage, and the anode or component of the installation, which acts as an anode. It is obvious that with such a design solution it is necessary to ensure reliable insulation of the anode from the housing, because in case of violation of such insulation there will be a real threat of electric shock. In the case of using BATR SPC power supply of electrodes is a single-phase current, the design of the transformer is significantly simplified, and the cost is reduced by at least three times. Similarly, it would be logical to manufacture and apply a single-phase voltage regulator, which in combination with a single-phase transformer will inevitably have a positive impact on the cost of the entire installation. This will reduce depreciation costs, which will also have a positive impact on cost. The lack of a rectifier and a ballast rheostat makes a certain contribution to reducing the cost of installations. From this analysis there is a question of reaching the temperature of the nitrided surface necessary for carrying out the planned technological mode. If this task cannot be performed, additional heaters can be used to ensure the independence of the discharge energy parameters. Thus, it is possible to use technological modes with high discharge voltage or current, which allow to form the necessary under the conditions of subsequent operation of the phase structure of the surface modified layer. The next task of the staging nature is the study of the electrical characteristics of the process, which is associated with the need to establish the magnitude of the ignition voltage of the discharge and its stable combustion in the anomalous mode. It is also necessary to establish analytical or experimental dependences of the parameters of the technological regime, taking into account its energy characteristics and thus establish the limits of energy characteristics necessary for the implementation of the process. The next question is to study the process of formation of a given phase structure in BATR HRC. The essence is that the nitriding process is always a combination of individual subprocesses: the formation of nitrides, surface spraying and diffusion of nitrogen into the depth of the surface layer. With normal nitriding (direct current), an equilibrium is established between the individual sub-processes, usually in favor of nitride formation and diffusion. The process in the conditions of this equilibrium takes place stationary and with different intensity, which depends not only on the energy conditions, but also on the material of nitrided parts. It is known that chromium steels can be nitrided only in gaseous media, where the neutral component predominates. This is because chromium is a nitrogenous material. Already in the initial period of nitriding, a monolayer of nitrogen is formed on the surface, which then acts as a barrier to the penetration of nitrogen into the depth of the surface. Nitriding is almost non-existent and the thickness of the nitride layer is very small. Given the significant relative duration of the half-life of the negative voltage (0.02 s) on the electrodes of the chamber, it is appropriate to hope that under the action of electron flow the nitride monolayer will be destroyed, and in the next half-period when the flow is directed to the cathode (detail) , will promote the intensification of both nitride formation and diffusion of nitrogen into the depth of the surface layer. Therefore, in principle, nitriding in a glow discharge with power supply of industrial frequency is possible. This significantly simplifies and reduces the cost of installation for the process.

Device for increasing the wear resistance of steels by nitriding in ACR with AC

The process of nitriding parts in the glow discharge is mainly carried out using a constant power supply discharge. Thus, when using a discharge with constant power on the outer surface of the part for a relatively short period of time (duration of the nitriding process 4 h), you can get a modified surface with specified properties with high stability of the discharge. The big disadvantage of this process is that parts of complex configuration (with a large number of small holes, with narrow slits, with sharp tops) require proper preparation of these parts for nitriding. All these holes and crevices must be properly closed because they significantly complicate the nitriding process using a constant discharge power supply and can provoke corona and arc discharges, which leads to overheating of the part and in most cases the nitriding process itself becomes impossible. Therefore, one of the options to solve this problem is to use a glow discharge with non-stationary power supply. When using AC industrial frequency, you do not need to create new equipment, but only need to upgrade existing ones. The essence of the modernization is to replace the uninterruptible power supply of the discharge with a source of non-stationary power supply of the discharge with alternating current of a given frequency. Adjusting the switching frequency, or as it is called duty cycle, is the ratio of the cycle period to the signal duration, and the shape of the signal itself makes it possible to influence the results of surface treatment. The influence of the shape and frequency of the discharge power signal on the nitriding process is due to the shutdown of the electric field, which allows to change the flight trajectory of the incident flux particles. That is, the switched off electric field allows the particles to move for some time by inertia along the tangent to their trajectory and allows the particles to penetrate to a much greater depth. And also to influence impossibility of transition of a glowing category in an arc. The use of cyclically switched AC power discharge makes it possible to nitriding parts with slits, with small diameter holes without the use of special equipment and you can not be afraid of corona and arc discharges. As a disadvantage, it should be noted that the nitriding process itself increases at least two or more times. The device for nitriding in a glow discharge with a direct current consists of a power supply to the chamber which contains a thyristor voltage regulator, a rectifier, a transformer, current and voltage sensors, a ballast rheostat, an automatic shut-off unit. The disadvantage of this device is its complexity and significant energy losses on the current converter, the need to use special filters to smooth the current. The work is based on the task of creating a device for nitriding in the glow discharge with AC power, which provides the opportunity to significantly simplify the equipment and, accordingly, reduce its cost. The problem is solved by the fact that the device for nitriding in the glow discharge introduced a source with non-stationary power supply with alternating current of a given frequency [8]. The purpose of the proposed device is primarily to significantly simplify the design of the installation for nitriding in the glow discharge and increase its reliability, as well as to reduce the cost of equipment, which is solved by replacing a constant discharge power supply with non-stationary AC power supply. This increases the reliability of the installation, and also due to a significant reduction in electricity losses reduces the cost of processing nitrided parts. The use of alternating current also affects the course and results of nitriding, as periodic changes in the polarity of the electrodes of the chamber contributes to the cleaning of the surface from the adsorption layer, which in turn leads to a significant change in phase composition of the surface modified layer [9]. The possibility of using the claimed device for conducting BATR on the existing industrial installation was experimentally tested. At the same time, the need for electricity significantly decreased due to the absence of losses for rectification, which also led to a reduction in the cost of processing. Analysis of the results of metallographic studies of the modified layer indicated the presence of a more uniform gradient of hardness in depth (gradient decreased by 1.7 - 3.5 times), which, in turn, increases the wear resistance of parts and quality performance of parts (Ukrainian patent №118327).

Method of nitriding in ACR with AC power supply

The most common method of BATR surface in which the part throughout the process serves as a cathode powered by a DC source. The disadvantage of this method is that its implementation is possible in the presence of an adjustable DC source, as well as special control devices. The problem of developing a method of nitriding in a glow discharge with AC power, which would simplify the process power supply, is solved by powering the process from an AC power source, the voltage should vary depending on the parameters of the technological mode of surface modification. The essence of the proposed idea is that the part and body of the camera or its special shell, which serve as electrodes, receive power of different polarity, and parts of the cage and the body of the camera or its special part, which acts as electrodes, are powered by AC power source , and the voltage varies depending on the parameters of the technological mode of modification of the surface of the parts. Unlike traditional incandescent nitriding methods, in which the part is always the cathode and the chamber shell or its special part serves as the anode, there is a constant threat of the incandescent discharge in the arc, which also complicates the process because the part is damaged locally or the entire surface. In addition, it is impossible to obtain a stable constant supply of the electrodes of the discharge chamber, ie to some extent the process takes place when supplied with non-constant current, although stable polarity. The experiments performed on the existing industrial plant indicate the possibility of implementing the claimed method of nitriding in a glow discharge with AC power supply of industrial frequency. If necessary, the frequency of the current can be easily changed using a simple frequency converter using an electromechanical device. In this case, the process of regulating the parameters of the technological process is significantly simplified, the reliability of technology implementation is increased, which has a positive effect on the cost of processing metal parts [10]. The idea of using industrial frequency AC as a power source for BATR, the possibility of switching the shape of pulses, changing their polarity has led to the development of a number of developments in methods and technologies of nitriding [10, 11].

Main results and conclusions

At BATR in CCR with supply of current of industrial frequency the installation for realization of process becomes cheaper. The latter factor will contribute, among other aspects, to the wider introduction of BATR technologies.

The use of alternating current affects the course and results of nitriding, as periodic changes in the polarity of the electrodes of the chamber contributes to the cleaning of the surface from the adsorption layer, which positively affects the nature of nitrogen saturation (gradient of microhardness times), contributes to a significant change in the phase composition of the surface modified layer and allows to expand the technological capabilities of nitriding in the direction of obtaining the required performance characteristics of working surfaces, in particular tribological characteristics.

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Стечишина Н.М., Стечишин М.С., Мартинюк А.В., Гладкий Я.М. Безводневе азотування в тліючому розряді з живленням змінним струмом

У роботі обгрунтована та експериментально показана можливість проведення безводневого азотування в тліючому розряді (БАТР) із живленням змінним струмом промислової частоти (СПЧ), а також можливості комутації форми імпульсів, зміни їх полярності, що вирішується введенням пристрою для азотування в тліючому розряді з джерелом живленням зі змінним струмом заданої частоти. При цьому аналіз результатів металографічних досліджень модифікованого шару вказав на наявність більш рівномірного градієнту твердості по глибині (градієнт знизився в 1,7 - 3,5 рази), що підвищує зносостійкість деталей та якісні показники зміцнення деталей з одночасним зниженням собівартості обробки та вартості установки

Ключові слова: азотування, змінний струм, циклічно-комутований розряд

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Research of the impact of carbon content in the auger material on its wear during dehydration in the solid waste garbage truck through regression analysis

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Abstract

The article is devoted to the study of the influence of carbon content in the auger material on its wear during dehydration of municipal solid waste in the garbage truck. Using the method of regression analysis, the hyperbolic regularities of screw wear depending on the carbon content in its material for different values of the friction path were determined. Graphical dependences of auger wear were constructed, depending on the carbon content in its material for different values of the friction path, which confirms the sufficient convergence of the obtained patterns. Carrying out additional regression analysis allowed to obtain the pattern of wear of the auger, depending on the carbon content in its material and the friction path, which established the following. After two weeks of operation and wear of the auger during the dewatering of solid waste in the garbage truck, increasing the carbon content in the auger material from 0.2% to 2.1% leads to a decrease in the energy intensity of dehydration of solid waste from 19.6% to 4.4 %, which makes the process of dehydration in the garbage truck cheaper. The graphical dependence of the reduction of energy consumption of dehydration of solid household waste due to increased carbon content in the auger material during its two-week wear is presented. The practicality of further research is to determine the rational material of the auger and ways to increase its wear resistance.

Key words: wear, carbon content, auger press, garbage truck, dehydration, municipal solid waste, regression analysis.

Introduction

In municipal engineering, an important task is to increase the wear resistance and reliability of machine parts [1, 2]. One of the promising technologies for primary processing of municipal solid waste (MSW), aimed at reducing both the cost of solid waste transportation MSW and the negative impact on the environment is their dehydration with accompanying processes of pre-compaction and partial grinding during loading into the garbage truck. In the garbage truck dehydration of MSW is performed by a conical screw, the surface of which is intensively worn out due to the available friction. This is due to the fact that MSW contains, in particular, components such as metal, glass, ceramics, stones, bones, polymeric materials, which can be attributed to abrasive materials, because they have different shapes, sizes and hardness, and available in MSW moisture 39-92% by weight creates an aggressive corrosive environment. Therefore, the study of the impact of carbon content in the auger material on its wear during dehydration of municipal solid waste in the garbage truck is a pending task

Literary review

The work [3] contains the results of experimental studies of wear resistance of different auger materials with different thermal and chemical-thermal treatment in corrosive-abrasive medium on special friction machines that simulated the operating conditions of extruders in the processing of feed grain with saponite impurities. The authors found that the wear resistance of materials in corrosive and abrasive environments at elevated temperatures depends not only on the hardness of the friction surface, but also on its structure and phase composition and changes in the hardness gradient along the depth of the hardened layer. To ensure high wear resistance of extruders in the manufacture of animal feed with admixtures of the mineral saponite, it is recommended to use for the manufacture of parts of the extruder unit steel KH12, reinforced by nitro hardening technology.

The authors of [4] investigated the effect on the properties of steel of its main elements (carbon and manganese), as well as alloying and modification of active carbide-forming and stabilizing austenite elements (chromium, titanium, boron). It is noted that the high carbon content contributes to the formation of carbides such as Me_xC_y, increase the wear resistance of steel and improve the casting properties.

In work [5], a mathematical model for calculating the rate of wear of triboelements in the tribosystem under conditions of corrosion and abrasive wear is proposed. The authors considered: active acidity, abrasiveness, roughness, load and sliding speed as input factors. Theoretically, the degree of influence of the above factors on the wear rate is established. It was found that abrasiveness is the most important factor, followed by the degree of decline – the level of active acidity and load.

The new design of the auger with a sectional elastic surface to reduce the degree of damage to the grain material during its transportation is presented in the article [6]. Concluded theoretical calculation of the interaction of the gran with the elastic section of the auger. A dynamic model has been developed to determine the influence of structural, kinematic and technological parameters of elastic auger on time and path of free movement of bulk material particles during their movement between sections, as well as to exclude the possibility of grain material interaction with non-working surface of auger working body.

The authors of [7] determined that to restore the screw requires surfacing or spraying a layer of a certain thickness on the end part of the screw coil, while the width of the restored layer is usually a few millimeters. An algorithm for selecting the optimal composite powder material for plasma spraying is described to increase the wear resistance of the working surfaces of machine parts, particularly the auger. Plasma spraying of composite powder materials, according to the authors, will increase the durability of the auger by 2-3 times, which will reduce the cost of repairs tenfold.

The influence of geometric parameters on the performance and design of a briquetting machine using a pressure model based on the theory of piston flow was studied in [8]. An analytical model using the pressure model was also developed based on Archard's wear law to study the wear of augers of biomass briquetting machines. The developed model satisfactorily predicted the wear of the auger and showed that the greatest influence on it are the speed of rotation and the choice of material. The amount of wear increases exponentially until the end of the auger, where the pressure is highest. Changing the auger design to select the optimal geometry and speed with the appropriate choice of material can increase the life of the auger and the productivity of the biomass briquetting machine.

Work [9] contains an analysis of the process of screw briquetting of plant materials into fuel and feed. Regularities of this process are necessary to determine the rational parameters of the working bodies. When designing briquette presses, it is necessary to consider the deformation of biomass, taking into account changes in physical and rheological properties at the time of interaction with the screw mechanism.

The article [10] investigated the wear of a twin-screw extruder of rigid PVC resins. The pressures around the cylinder were measured by extrusion of two rigid PVC resins. In a laboratory extruder with a diameter of 55 mm, the forces acting on the screw core are determined. Numerical simulation of the flow was performed using the degree parameters of the viscosity of the resins.

The process of pressing wood chips in screw machines was studied in [11]. The processes occurring in different parts of the auger are established, formulas are determined that allow to calculate the loads acting on the auger turns, as well as to determine the power required for pressing. The specific energy consumption and the degree of heating of raw materials during pressing are set.

In work [12], the results of experimental studies of the MSW dehydration process based on the planning of an experiment by the Box-Wilson method are presented. Rotary central regression planning was used to obtain quadratic regression equations with 1st order interaction effects for such objective functions as humidity and density of pre-compacted and dehydrated MSW, maximum drive motor power, MSW dehydration energy consumption. This allowed to determine the optimal parameters of dewatering equipment by minimizing the energy consumption of the process (screw speed, the ratio of the radial gap between the auger and the housing, as well as the ratio of the auger core diameter to the outer diameter of the screw on the last turn) for both mixed and "wet" MSW.

The materials of the article [13] proposed an improved mathematical model of solid wastewater dewatering in the garbage truck, taking into account the wear of the auger, which allowed to numerically study the dynamics of this drive during start-up, and determine that increasing auger wear increases the pressure of the speed and speed of the auger are significantly reduced. The degree regularities of the change of nominal values of pressures at the inlet of the hydraulic motor, angular velocity and frequency of rotation of the auger from the values of its wear are determined, the last of which describes the debugging from the optimal speed of the auger in the process of its wear and is used to determine the energy consumption of dehydration of solid waste, taking into account the wear of the auger. It is established that the wear of the auger by 1000 μm leads to an increase in the energy consumption of solids dehydration by 11.6%, and, consequently, to the rise in the cost of their dehydration in the garbage truck and speed up the wear process.

In [14], the influence of surface hardness of the auger on its wear during dehydration of MSW in a garbage truck was investigated by regression analysis, and also found that during two weeks of operation and wear of the auger during dehydration of solid waste in the garbage truck increase in the hardness of the auger surface from 2310 MPa to 10050 MPa leads to a decrease in energy consumption of solid waste dehydration from 16.7% to 1.5%, and, hence, to reduce the cost of the process of dehydration in the garbage truck

Purpose

Investigation of the influence of carbon content in the auger material on its wear during dehydration of solid household waste in the garbage truck.

Methods

Determination of paired regularities of screw wear from carbon content in its material was performed by regression analysis [15]. Regressions were determined on the basis of linearizing transformations, which allow to reduce nonlinear dependence to linear one. The coefficients of regression equations were determined by the method of least squares with the help of the developed computer program "RegAnaliz", which is protected by a copyright registration certificate for the work.

The following regularities were used to determine the energy consumption of MSW dehydration taking into account the wear of the auger [13]:

$$E = 1504 - 15.92 w_0 + 0.3214 \rho_0 - 1.069 n(u) - 2061(\Delta_{aug} + u)/(D_{\min} - 2u) - 1947(d_{\min} - 2u)/(D_{\min} - 2u) + 9.118 \cdot 10^{-4} w_0 \rho_0 + 0.002142 w_0 n(u) + 18.12 w_0 (\Delta_{aug} + u)/(D_{\min} - 2u) - 2.115 w_0 (d_{\min} - 2u)/(D_{\min} - 2u) + 4.392 \cdot 10^{-4} \rho_0 n(u) - 2.005 \rho_0 (\Delta_{aug} + u)/(D_{\min} - 2u) + 0.3361 \rho_0 (d_{\min} - 2u)/(D_{\min} - 2u) + 0.09031 w_0^2 - 7.923 \cdot 10^{-4} \rho_0^2 + 0.,008241 n(u)^2 + 104172 [(\Delta_{aug} + u)/(D_{\min} - 2u)]^2 + 1318 [(d_{\min} - 2u)/(D_{\min} - 2u)]^2 \ [\text{kWh/tons}]; \quad (1)$$

$$n = 52.43 - 1.276 \cdot 10^{-3} u^{1.5} \ [\text{rpm}], \quad (2)$$

where E – is the energy consumption of solid waste dehydration, kW·h/tons; ρ_0 – initial density of solid waste, kg/m^3; w_0 – initial relative humidity of solid waste, %; n – the nominal speed of the auger, rpm; u – auger wear, m; Δ_{aug} – radial clearance between auger and housing, m; d_{min} – outer diameter of the auger on the last coil, m; D_{min} is the diameter of the auger core on the last coil, m.

Results

The values of auger wear for different values of carbon content in its material and the friction path are given in table. 1 [3].

Table 1

Auger wear values for different values of carbon content in its material and friction path [3]

No	Steel grade and heat treatment	The carbon content in the auger material, %	Wear, μm for friction path, m			
			3000	6000	9000	12000
1	steel 20 without heat treatment	0.2	68	132	195	258
2	steel 45 hardening	0.45	53	103	153	203
3	steel U8 hardening	0.8	48	91	134	177
4	steel SHKH15 hardening	1	43	80	116	152
5	steel KH12 hardening	2.1	39	72	105	138

As a result of regression analysis of the data in table 1 determined the hyperbolic patterns of wear of the auger depending on the carbon content in its material for different values of the friction path:

$$u_{s=3000} = 37.9 + \frac{6.181}{C_C}; \quad (3)$$

$$u_{s=6000} = 70.08 + \frac{12.82}{C_C}; \quad (4)$$

$$u_{s=9000} = 102.2 + \frac{19.31}{C_C}; \quad (5)$$

$$u_{s=12000} = 134.3 + \frac{25.8}{C_C}, \quad (6)$$

where u – wear, μm; C_C – carbon content in the auger material, %; s – path of friction, m.

Figure 1 shows the graphical dependences of auger wear depending on the carbon content in its material for different values of the friction path, constructed using dependences (3 – 6), confirming the sufficient convergence of the obtained patterns compared to the data in table 1.

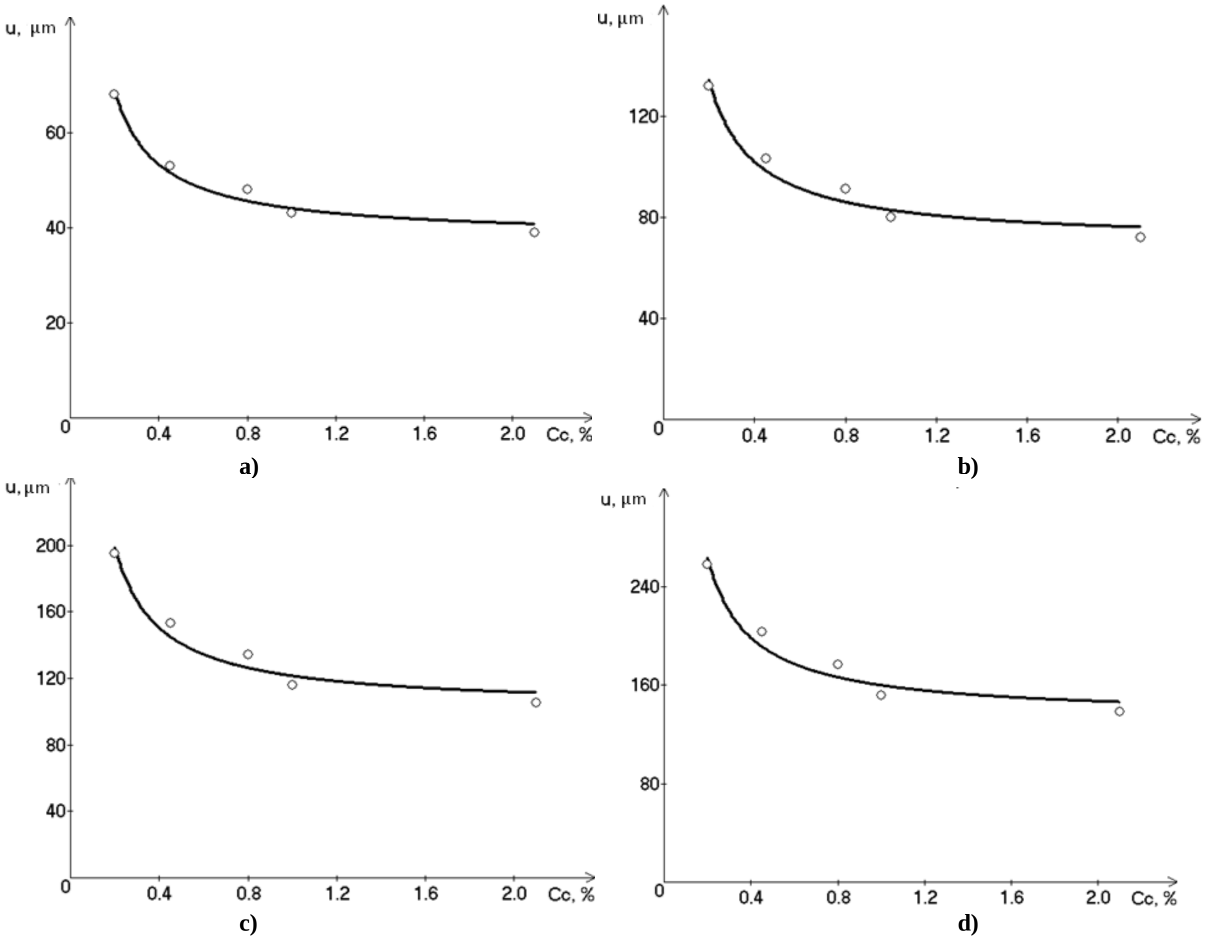


Fig. 1. The wear of the auger depending on the carbon content in its material for different values of the friction path (a) – *s* = 3000 m, (b) – *s* = 6000 m, (c) – *s* = 9000 m, (d) – *s* = 12000 m: actual ○, theoretical —

Regularities (3 - 6) for different values of the friction path can be written in general as follows

$$u = A(s) + \frac{B(s)}{C_C}, \quad (7)$$

where A (s), B (s) are the regression coefficients that depend on the friction path.

After additional regression analysis, the regression coefficients that depend on the friction path can be described by linear laws:

$$A(s) = 5.79 + 0.01071s; \quad (8)$$

$$B(s) = 0.002178s - 0.309. \tag{9}$$

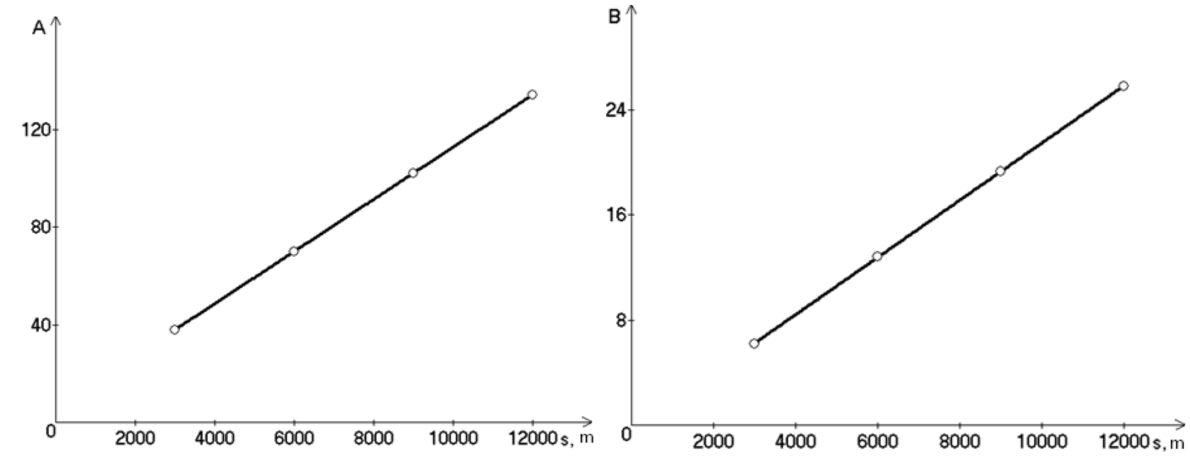
The results of the regression analysis are shown in Table 2, where the cells with the maximum values of the correlation coefficient R for each of the paired regressions are marked in gray.

Figure 2 shows the graphical dependences of the regression coefficients on the friction path, constructed using the dependences (8, 9), which confirm the sufficient convergence of the obtained regularities.

Table 2

The results of regression analysis of the dependence of the wear of the auger depending on the carbon content in its material for different values of the friction path

No	Type of regression	Correlation coefficient R for paired regressions					
		$u_{s=3000}=f(C_C)$	$u_{s=6000}=f(C_C)$	$u_{s=9000}=f(C_C)$	$u_{s=12000}=f(C_C)$	$A=f(s)$	$B=f(s)$
1	$y = a + bx$	0.83755	0.84605	0.84762	0.84820	0.9999998	0.99998
2	$y = 1 / (a + bx)$	0.91045	0.91891	0.91715	0.91595	0.9385673	0.92340
3	$y = a + b / x$	0.98738	0.98299	0.97928	0.97723	0.9289544	0.93077
4	$y = x / (a + bx)$	0.96886	0.96886	0.96839	0.96839	0.9407220	0.84683
5	$y = ab^x$	0.87626	0.88527	0.88527	0.88501	0.9831751	0.97792
6	$y = ae^{bx}$	0.87626	0.88527	0.88527	0.88501	0.9831751	0.97792
7	$y = a \cdot 10^{bx}$	0.87626	0.88527	0.88527	0.88501	0.9831751	0.97792
8	$y = 1 / (a + be^{-x})$	0.96524	0.97832	0.97832	0.96832	0.9883223	0.98832
9	$y = ax^b$	0.96652	0.97839	0.97839	0.96839	0.9998737	0.99993
10	$y = a + b \cdot \lg x$	0.97417	0.97800	0.97798	0.96775	0.9802967	0.98124
11	$y = a + b \cdot \ln x$	0.97417	0.97800	0.97798	0.96775	0.9802967	0.98124
12	$y = a / (b + x)$	0.91045	0.91891	0.91715	0.91595	0.9385673	0.92340
13	$y = ax / (b + x)$	0.94810	0.93476	0.92777	0.92406	0.9996063	0.99989
14	$y = ae^{b/x}$	0.97160	0.96307	0.95757	0.95460	0.9805651	0.98556
15	$y = a \cdot 10^{b/x}$	0.97160	0.96307	0.95757	0.95460	0.9805651	0.98556
16	$y = a + bx^n$	0.69931	0.70792	0.70891	0.70924	0.9842758	0.98346



a) b)

Fig. 2. Dependences of regression coefficients on the path of friction (a) - A = f (s), (b) - B = f (s): actual ○, theoretical —

After substituting the laws (8, 9) into the dependence (7), we obtain the law of wear of the auger depending on the carbon content in its material and the friction path

$$u = 5.79 + 0.01071s + \frac{0.002178s - 0.309}{C_C}. \tag{10}$$

Figure 3 shows the graphical dependence of auger wear in the plane of the impact parameters: the carbon content in its material and the friction path.

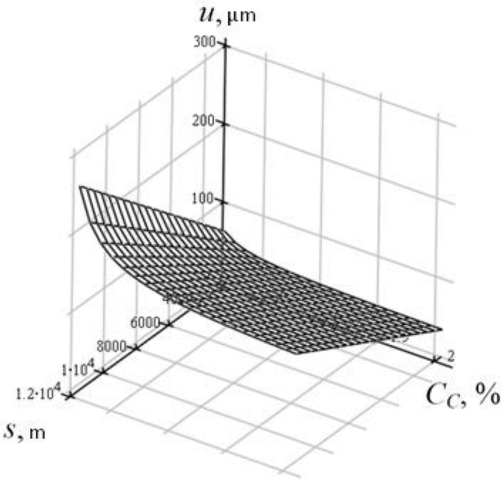


Fig. 3. Dependence of screw wear *u* in the plane of impact parameters: carbon content in its material C_C and friction path *s*

Figure 4 shows the graphical dependence of the carbon content in the auger material of the solid waste management device on the energy intensity of the process (with its two-week wear *s* = 56850 m [14]), constructed using regularities (1, 2, 10).

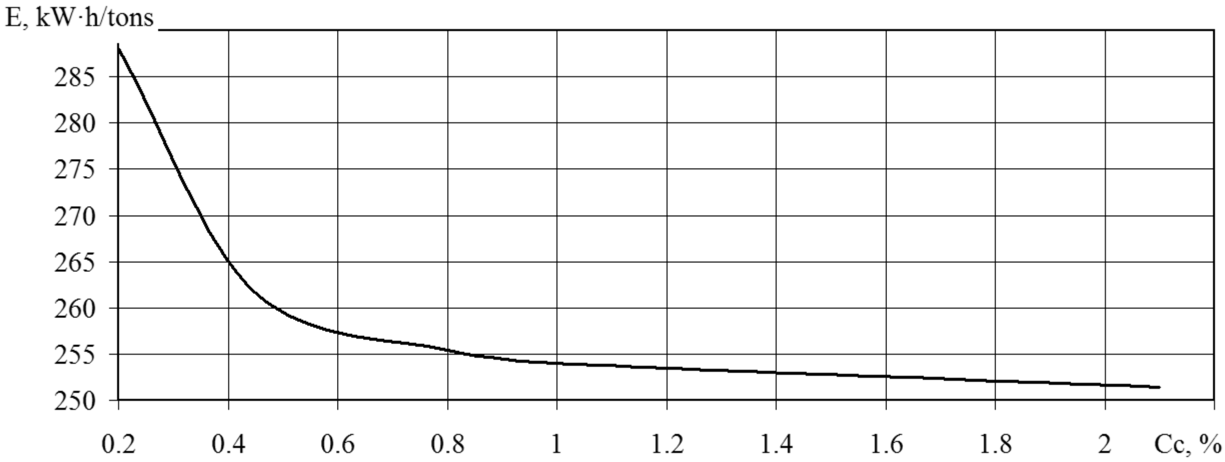


Fig. 4. The effect of increasing the carbon content in the auger material on reducing the growth rate of energy consumption of the dehydration process MSW after its two-week operation and wear (*s* = 56850 m)

Figure 4 shows that after two weeks of operation and wear of the auger during MSW dehydration in the garbage truck, the increase in carbon content in the auger material from 0.2% to 2.1% leads to a decrease in the energy intensity of MSW dehydration from 19.6% to 4.4% , and, consequently, to reduce the cost of dehydration MSW in the garbage truck. Due to carburizing surfacing, it is possible to increase the carbon content in the surface layers up to 6%, forming a composite metal-carbide surface. Therefore, the determination of the rational composition and structural state of the material of the friction surfaces of the auger and ways to increase its wear resistance require further research.

Conclusion

The hyperbolic regularities of auger wear depending on the carbon content in its material for different values of the friction path were determined. Carrying out additional regression analysis allowed to obtain the pattern of wear of the auger depending on the carbon content in its material and the friction path, which showed that during two weeks of operation and wear of the auger during dehydration of solid waste, in the garbage increase carbon content in the auger material from 0, 2% to 2.1% leads to a decrease in the growth rate of energy consumption of solid waste dehydration from 19.6% to 4.4%, and, consequently, to a reduction in the cost of the process of dehydration in the garbage truck. Due to carburizing surfacing, it is possible to increase the carbon content in the working layers to the formation of supereutectic iron-carbon alloys with the formation of a composite metal-carbide surface. Therefore, the definition of rational auger material and ways to increase its wear resistance requires further research.

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Березюк О.В Савуляк., В.І., Харжевський В.О., Осадчук А.А. Дослідження за допомогою регресійного аналізу впливу вмісту вуглецю в матеріалі шнека на його знос під час зневоднення у сміттєвозі твердих побутових відходів

Стаття присвячена дослідженню впливу вмісту вуглецю в матеріалі шнека на його знос під час зневоднення твердих побутових відходів у сміттєвозі. За допомогою використання методу регресійного аналізу визначено гіперболічні закономірності зносу шнека залежно від вмісту вуглецю в його матеріалі для різних значень шляху тертя. Побудовано графічні залежності зносу шнека залежно від вмісту вуглецю в його матеріалі для різних значень шляху тертя, що підтверджують достатню збіжність отриманих закономірностей. Проведення додаткового регресійного аналізу дозволило отримати закономірність зносу шнека залежно від вмісту вуглецю в його матеріалі та шляху тертя, за допомогою якої встановлено, що при двотижневій експлуатації та зношуванні шнека під час зневоднення твердих побутових відходів у сміттєвозі збільшення вмісту вуглецю в матеріалі шнека з 0,2% до 2,1% призводить до зниження темпів зростання енергоємності зневоднення твердих побутових відходів з 19,6% до 4,4%, а, отже, і до здешевлення процесу їхнього зневоднення у сміттєвозі. Представлена графічна залежність зниження енергоємності зневоднення твердих побутових відходів внаслідок збільшення вмісту вуглецю в матеріалі шнека при його двотижневому зношуванні. Виявлено доцільність проведення подальших досліджень з визначення раціонального матеріалу шнека та шляхів підвищення його зносостійкості.

Ключові слова: знос, вміст вуглецю, шнековий прес, сміттєвоз, зневоднення, тверді побутові відходи, регресійний аналіз

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Ways to increase the wear resistance of pistons of internal combustion engines (review)

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Abstract

The article analyzes the materials from which the piston is made for internal combustion engines. For automobile and tractor engines, in particular, eutectoid mixtures of the AL25 type and eutectoid mixtures containing copper, nickel, magnesium and manganese are used. The chemical composition of aluminum alloys is given. Pistons for high-speed, forced diesel, medium-speed engines are made of gray or malleable cast iron (SCh24-44, SCh28-48, SC32-53), as well as alloyed with additives of vanadium, chromium, titanium, copper (RF45-5). Heat-resistant steels of the 20Kh3VMF type are used for combined pistons. Research work is being carried out on pistons made of titanium and carbon fiber. Pistons with automatic adjustment of the degree of compression can limit the thermal and mechanical stress of the parts of the cylinder-piston group, boost the engine at an average effective pressure of 1.5-2 times, improve starting quality, provide the ability to use different brands of fuel. A combined piston with copper-fluoroplastic inserts is available for internal combustion engines, compressors, pumps and other reciprocating machines. Inserts made of copper-fluoroplastic composition provide the application of a thin film of copper on the friction surface throughout the life of the engine, which significantly accelerates running, reduces burrs and abrasions, increases wear resistance and durability of CNG parts. The main disadvantages and advantages of the performance characteristics of pistons made of different materials. The analysis of designs of pistons is made. The main requirements for the design of pistons are: simplicity of design, and if possible to ensure symmetry about the axis of the cylinder, minimum weight, maximum strength and rigidity, wear resistance of the material, efficient heat dissipation (cooling); minimum cost of production. The main defects of the piston are: the height of the first groove, the diameter of the hole under the piston pin, the diameter of the skirt.

Key words: engine, piston, fluoroplastic, construction, wear resistance, piston skirt, restoration, deformation, remelting, cylinder, strength, rigidity, durability.

Materials for pistons

For the manufacture of pistons, depending on the purpose of the engine and type of construction, use cast iron, steel, aluminum alloys. For automobile and tractor engines, in particular, eutectoid mixtures of AL25 type (11-13% Si) and eutectoid mixtures containing copper, nickel, magnesium and manganese are used.

Pistons of these alloys are made by casting into the ground or in the chill mold, the latter method allows you to more accurately withstand the weight of the workpiece, reduce the allowance for machining. Pistons are also stamped from alloys AK-4, AK4-1, AK2, D20, which have high properties at elevated temperatures (300°C). The chemical composition of materials for aluminum-based pistons are shown in table 1.

Pistons for high-speed, forced diesel, medium-speed engines are made of gray or malleable cast iron (СЧ24-44, SCh28-48, SCh32-53), as well as alloyed with additives of vanadium, chromium, titanium, copper (ВЧ45-5).

Heat-resistant steels of the 20Kh3MVF type are used for combined pistons. Pistons made of cast iron and steel are characterized by greater strength, wear resistance and lower coefficient of thermal expansion compared to aluminum alloys. Their use reduces the gaps between the piston skirt and the sleeve. The main disadvantages of cast iron and steel pistons are increased wear of the cylinder mirror, low thermal conductivity (3-4 times less than aluminum alloys), greater weight (30-50% more than aluminum pistons).

Table 1

Chemical composition of aluminum alloys for pistons of tractor engines

Brand of alloys	Chemical composition of the main components									
	AL	Mg	Si	Mn	Cu	Ni	Ti	Cr	Fe	Zn
AL-1	basis	1,25-1,75	–	–	3,7-4,5	1,75-2,25	–	–	–	–
AL -11	basis	0,1-0,3	6,0-8,0	–	–	–	–	–	0,8-1,2	10-14
AL 24	basis	1,5-2,0	–	0,2-0,5	–	–	0,1-0,2	–	–	–
AL 25	basis	0,8-1,3	11,0-13,0	0,3-0,6	1,5-3,0	0,8-1,3	0,05-0,2	–	–	–
AL 30	basis	0,8-1,3	11,0-13,0	–	0,8-1,5	0,8-1,3	–	–	–	–
AL 21	basis	0,8-1,3	–	0,15-0,25	4,6-6,0	2,6-3,6	–	0,1-0,2	–	–
VKZLS -2	basis	0,2-0,5	20,0-22,0	0,20-0,40	2,2-3,0	2,2-2,8	0,1-0,3	0,2-0,4	–	–
AK4	basis	1,4-1,8	0,5-1,2	–	1,9-2,5	0,8-1,3	–	–	0,8-1,3	–
AK4-1	basis	1,2-1,8	–	–	1,9-2,7	0,8-1,4	0,02-0,1	–	0,8-1,4	–

Noteworthy is the research work on titanium and carbon fiber pistons. So in the USA [1] the patented engine with pistons, piston rings, cylinder liners and cylinder blocks is made of carbon fiber. The engine significantly reduces the thermal gaps between the parts of the CNG, which in turn reduces the impact when relocating the pistons, the breakthrough of gases from the combustion chamber, emissions of unburned carbohydrates. In Germany [2] a piston made of carbon is proposed. The method of manufacturing carbon structural material involves pressing carbon granules under high pressure at high temperature. The carbon piston has a low coefficient of friction and thermal expansion, can work reliably in some modes in dry friction. The weight of the piston is much less than the weight of the metal pistons. The design of the piston with the use of carbon inserts in the walls of the piston skirt, receiving lateral loads, is also proposed.

Piston designs.

The piston of internal combustion engines is the most loaded part, as the temperature of the gases can reach 2500°C, and mechanical loads are close to shock. Temperature differences along the length of the piston cause thermal stresses that contribute to its deformation. The piston consists of the upper part (sealing) and lower (guide). The sealing part has piston rings that ensure the tightness of the working part of the cylinder, the guide (skirt) receives lateral loads. Basic requirements for the design of pistons:

1. Simplicity of a design, and if possible maintenance of symmetry concerning an axis of the cylinder;
2. Minimum weight, maximum strength and rigidity, wear resistance of the material;
3. Effective heat dissipation (cooling);
4. Minimum cost of production.

Pistons for carburetor engines are usually made of lightweight aluminum alloys with T-shaped and U-shaped slots (Fig. 1). Slots in the pistons reduce the gap between the piston and the sleeve, which significantly reduces shocks and vibrations during transfers and reduces the likelihood of jamming. In these pistons, the cross section is made in the form of an oval, the major axis of which is in the plane of oscillation of the connecting rod. Pistons with slots are used in engines with small cylinder diameters. Cast alloy pistons made of aluminum alloys with an annular cavity are also used for cooling (Fig. 2) with oil supplied through a nozzle [3]. These pistons are used in engines with a crankshaft speed of more than 2000 min^{-1}.

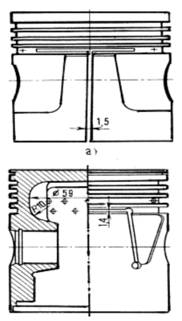

Fig.1. Monometallic pistons of carburetor engines: a) T-shaped; b) U-shaped form

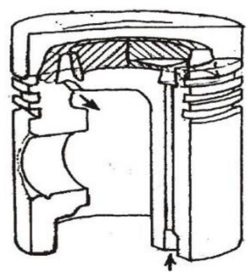

Fig. 2. The scheme of cooling the piston head

In forced diesels, the piston rod is stamped from an aluminum alloy, and the head is made of heat-resistant material (cast iron or alloy steel) [3]. In the engine 16ЧН48 / 58 with a decrease in the thickness of the steel head of the piston, the temperature in the area of the first annular groove decreased by 40 ° C. In fig. In Fig. 3 shows the design of the combined piston.In the construction of combined pistons use thermal insulation between the piston head and the cutting (Fig. 4).

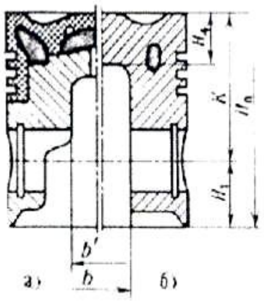

Fig. 3. Piston of forced diesels:a) combined; b) all-metal

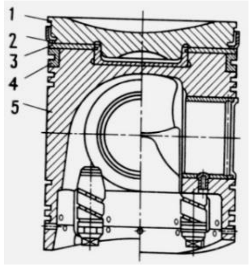

Fig. 4. Piston with heat pad and inseparable heat ring: 1 - head; 2 - inseparable heat ring; 3 - thermal insulation; 4 - ring holder; 5 - piston

For two-stroke high-power engines from Sulzer, in order to prevent overheating and trapping of the piston, forced rotation of the piston around its axis was used during engine operation [4]. With the help of a gear wheel, which is located in the middle of the piston body and two ratchets, which are located in the connecting rod, the movement of the connecting rod was converted into angular (cyclic) movement of the piston (Fig. 5). The ratchet wheel is connected to the piston by a plate spring, which ensures smooth rotation of the piston around the axis (about 10 min-1 at 500 revolutions of the crankshaft per minute). The connecting rod and the piston are connected by a ball bearing. To preserve the shape of the skirt of diesel pistons set compensating inserts in the form of ribbons (Fig. 6), which cover a significant part of the skirt [3].

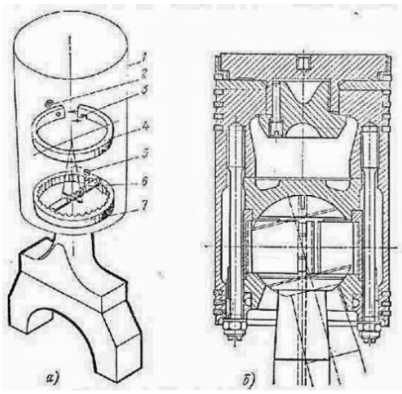

Fig. 5. Piston of the Sulzer engine: a) a sketch of the mechanism of rotation of the piston; b) piston design

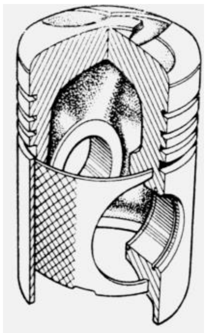

Fig. 6. Piston with thermostatic insert

Diesel pistons of diesel engines work in difficult conditions. There are a large number of different designs that differ in the shape of the head, the method of its attachment to the piston cutting, the type of cooling, the brand of material.mThe piston of the two-stroke diesel locomotive is presented in fig. 7. Its design feature is that instead of pins there is a snap ring, which is located in the light part of the skirt [3].

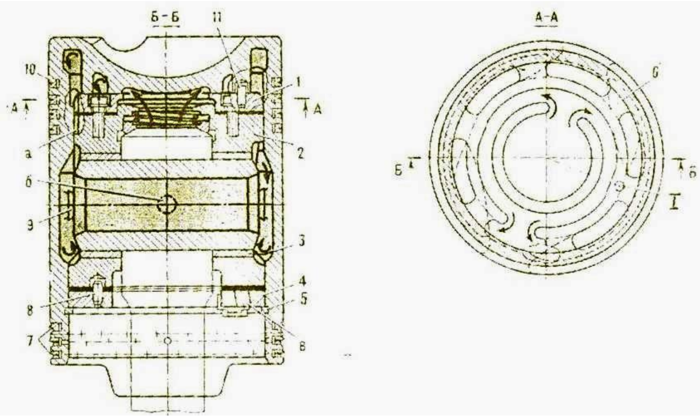

Fig. 7. The piston of the two-stroke diesel diesel engine 2D100: a, b, c - a groove and openings for oil exit from a head and a piston insert; 1 - top plate; 2 - insert; 3 - bushing; 4 - bottom plate; 5; 6 - radial rib;7 - oil removal ring; 8, 11 - pin; 9 - finger stops; 10 - compression ring

During the modernization of the engine L-V42M (ЧН42 / 45), as a result of which the cylinder power was increased to 625 kW, the company "MITSUI" used a lightweight piston, which consists of three parts (Fig. 8). The cast steel piston head is made with thinner walls and carries two of the three compression rings (there were four). Below the head is the main part, made of cast iron with ball-shaped graphite, on which is the third compression ring, as well as a bearing for the piston pin. The main part is a skirt made of aluminum alloy. The weight of the piston was reduced by 27%.

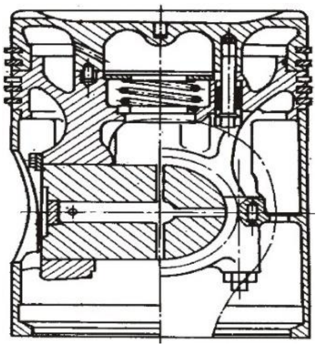

Fig. 8. Composite piston company "MITSUI"

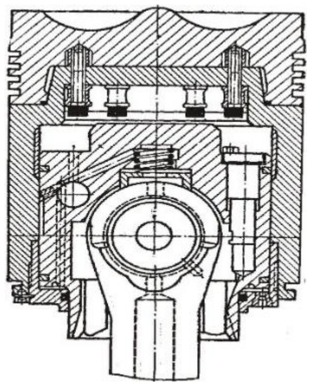

Fig. 9. Diesel piston with varying degrees of compression

The combined piston for the diesel with high forcing which provides a variable degree of compression at work is presented in fig. 9 [5]. Pistons with automatic adjustment of the degree of compression (Fig. 10) can limit the thermal and mechanical stress of the parts of the cylinder-piston group, boost the engine at an average effective pressure of 1.5-2 times, improve starting quality, ensure the use of different brands of fuel [6].

One of the promising methods of reducing the stress state and strengthening the pistons is the use of matrix inserts made of ceramic fibers, which are filled with molten magnesium alloy. In fig. In Fig. 11 shows a diagram of the piston where the head is reinforced with fibers 1 of Al_2O_3, and under the compressor rings filled with an insert of niresist 2.

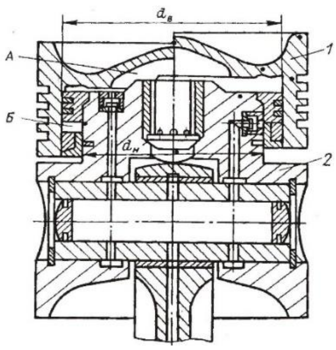

Fig. 10. Structural diagram of the piston with automatic adjusting compression ratio: 1 - piston shell; 2 - housing; A and B - respectively, the upper and lower hydraulic cavities

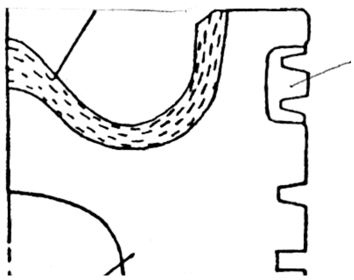

Fig. 11. Combined piston: Al_2O_3 fibers; niresist; piston (aluminum alloy)

In the United States [7], a piston is patented that has a wide outer annular non-metallic insert in the area of the piston pin lugs, which prevents direct contact of the skirt with the cylinder mirror. The insert is made of heat-resistant polymeric material with graphite filler and has a low coefficient of friction.

For internal combustion engines, compressors, pumps and other reciprocating machines, a combined piston [8-9] with copper-fluoroplastic inserts is offered (Fig. 12).

In the standard piston of a diesel engine with a wall thickness of 4 mm and more in the guide part (skirt) drilled two grooves in the form of a "swallowtail", in which inserts of composite polymeric material based on fluoroplastic F4.

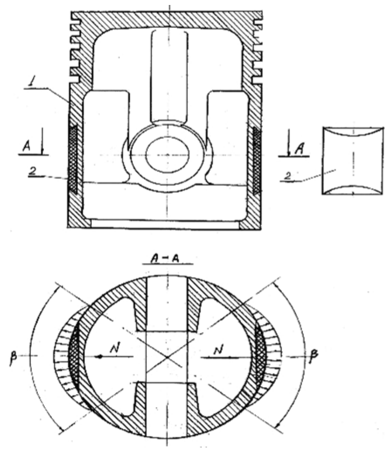

Fig. 12. Combined piston: 1 - piston; 2 - insert

Inserts of copper-fluoroplastic composition provide a thin film of copper on the friction surface throughout the service life (before overhaul) of the engine, which significantly speeds up running time, reduces burrs and abrasions, increases wear resistance and durability of CNG parts. The experimental sample of the piston of the YaMZ-236 engine is presented in fig. 13.

Fig. 13. Combined piston with copper-fluoroplastic inserts

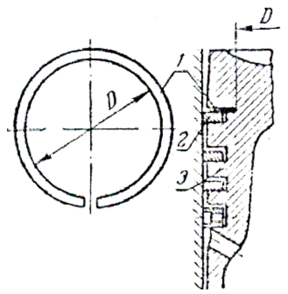

Fig. 14. Scheme of restoration of the coupling ring-piston groove: 1 - clamping ring; 2 - piston ring; 3 - piston

Ways to restore the pistons

The main defects of the piston are: the height of the first groove, the diameter of the hole under the piston pin, the diameter of the skirt.

Coupling - the first piston ring - the groove of the piston wears out the most. It was found [10] that 75% of worn pistons made of aluminum alloys have a defective defect of the upper groove, which is restored by boring, installing a ring of aluminum alloy, welding it with subsequent boring under the ring of nominal size. The holes for the piston pins are restored by boring to the repair size using a finger of increased diameter.

In individual production, the coupling "piston groove - upper piston ring" can be restored by the method of auxiliary repair dimensions, developed by prof. K.A. Achkasov. To do this, in the pre-drilled groove of the piston (Fig. 14) install a spring ring complete with a piston ring of nominal size. Spring rings are made of steel tape steel U-7 or U-8 by winding, followed by thermofixation. The thickness of the tape should be in the range of 0.75-1 mm, and the width should be equal to the size of the auxiliary groove above the first ring. Thermofixation temperature 400 ° C.

The method of electron rubbing [11] is used to restore the piston skirt and holes in the lugs under the piston pin. Restore the piston with skirt wear up to 0.15 mm.

The process of electron rubbing of the piston takes place at high current densities, which provides high productivity of the process. Iron-zinc electrolyte is used to restore pistons made of aluminum alloys. The anode is made of zinc. When using an iron-aluminum electrolyte, the anode is made of steel.

Technological process of restoration of pistons is carried out in the following sequence: after washing, cleaning from a deposit of pistons degrease in the electrolytic way at the following modes: current density - 0,4-0,6kA / m^2, electrolyte temperature 40 °C, processing time - 1-1,5 min. After rinsing in water, the piston is clarified in nitric acid (7-9 s).

In the bath ACS 1513 spend zinc treatment by immersing the pistons in a solution of zinc sulfate with a holding time of 1.5-2 min at 45-50 ° C.

Modes of electrofriction: piston speed - 30-40 min^{-1}, current density - 60-80 kA / m^2, electrolyte temperature - 45-50 ° C, pH acidity - 2.5-3, cooling rate - 0.01 mm / min.

The method of plastic deformation for the restoration of the piston skirt is proposed in [12]. We offer a special landing and leveling tool (Fig. 15) in the form of a roller knurler, which displaces the metal from the surface of the piston skirt and gives an increase in diameter of more than 0.2 mm. Profile notches form a rhombic grid, which is aligned by machining.

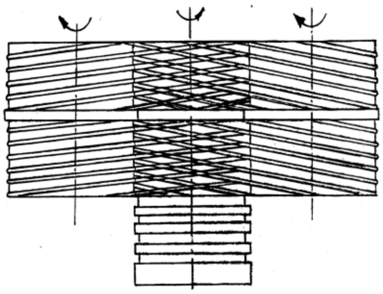

Fig. 15. Scheme of restoration of the piston skirt by plastic deformation

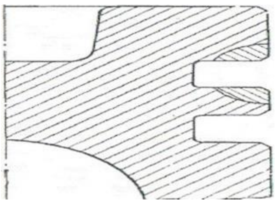

Fig. 16. Sealing of the upper groove of the piston by remelting by doping

Notches on the rollers of planting material provide the most favorable conditions for lubrication of friction surfaces.

The method of plasma remelting to restore and strengthen the piston grooves is that in the environment of argon gas melts part of the aluminum alloy with the simultaneous introduction of filler wire, which contains alloying elements (Fig. 16).

In the process of remelting, the alloying material interacts with the aluminum alloy with the formation of solid thermostable aluminides. Depending on the chemical composition of the piston and the number of alloying elements, the remelting strength increases by 1.2-1.3 times, hardness by 1.3-2 times, resistance by 1.5-4 times [13].

Conclusions

1. The analysis of materials from which pistons for internal combustion engines are made is made. The chemical composition of aluminum alloys is given.
2. For internal combustion engines, compressors, pumps and other reciprocating machines, a combined piston with copper-fluoroplastic inserts is offered.
3. The analysis of designs of pistons is made. The basic requirements for the design of pistons are presented. The main defects of the piston are presented.
4. The analysis of ways of restoration of pistons is made.

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Дудчак Т.В. Шляхи підвищення зносостійкості поршнів двигунів внутрішнього згоряння (огляд)

В статті зроблен аналіз матеріалів, з яких виготовляють поршня для двигунів внутрішнього згоряння. Для автомобільних і тракторних двигунів, зокрема, застосовують евтектоїдні суміші типу АЛ25 і заевтектоїдні, які містять мідь, нікель, магній та марганець. Приведений хімічний склад алюмінієвих сплавів. Поршні для швидкохідних, форсованих тепловозних, середньообертових двигунів виготовляють з сірого або ковкого чавуну (СЧ24-44, СЧ28-48,СЧ32-53), а також легованого присадками ванадію, хрому, титану, міді (ВЧ45-5). Для комбінованих поршнів застосовують жаростійкі сталі типу 20Х3МВФ. Проводяться дослідні роботи над поршнями з титану і вуглепластиків. Поршні з автоматичним регулюванням ступеню стиску дозволяють обмежити теплову і механічну напруженість деталей циліндро-поршневої групи, форсувати двигун по середньому ефективному тиску в 1,5-2 рази, покращити пускові якості, забезпечити можливість використання різних марок палива. Для двигунів внутрішнього згорання, компресорів, насосів та інших поршневих машин пропонується комбінований поршень з мідно-фторопластовими вставками. Вставки з мідно-фторопластової композиції забезпечують нанесення тонкої плівки міді на поверхні тертя на протязі всього ресурсу роботи двигуна, що значно прискорює припрацювання, зменшує задири і натири, збільшує зносостійкість і довговічність деталей ЦПГ. Дані основні недоліки і переваги експлуатаційних характеристик поршнів, виготовленних з різних матеріалів. Зроблен аналіз конструкцій поршнів. Представлені основні вимоги при конструюванні поршнів, це:простота конструкції, і по можливості забезпечення симетричності відносно осі циліндра;мінімальна маса, максимальна міцність і жорсткість, зносостійкість матеріалу;ефективний відвід тепла (охолодження); мінімальна собівартість виготовлення.

Ключові слова: двигун, поршень,фторопласт, конструкція, зносостійкість, юбка поршня, відновлення, деформування, циліндр, міцність, жорсткість, довговічність.

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Dependence of the elastic modulus of powder coatings on their porosity in electrical contact hardening

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Abstract

The relationship between the elastic modulus and the porosity of powder coatings has been investigated for different methods of their deposition. Porosity is the main means of assessing the quality of coatings and depends on the techniques for their production. A decrease in the elastic modulus of coatings after gas flame spraying is due to the presence of porosity to 30%, and after electric arc spraying – to 20%. The electric contact method of forming coatings makes it possible to reduce porosity to 5-6% and so to bring the value of the elastic modulus of coatings closer to that of compact materials.

Key words: electric contact method for forming coatings, powder coatings, porosity, elastic modulus, mechanical properties, adhesion strength.

Introduction

Porosity is an inherent feature for many types of powder coatings and is considered to be of their second (after adhesion strength), but in some cases, of the first order property. It is the main means of assessing the quality of coatings, especially corrosion-resistant and wear-resistant coatings, where its presence is undesirable. The porosity of coatings and its relationship with their mechanical properties, in particular with the elastic modulus (E), has long attracted the attention of researchers. Investigation of the mechanical properties of materials with coatings is one of the most important stages of researches, because this allows one not only to objectively interpret the behavior of parts during operation, but also to effectively control the resource of their service through influencing the composition, structure and, naturally, the conditions of obtaining them.

State of the problem

A significant decrease in the porosity of coatings can be achieved by thermal hardening. However, it should be noted that in some cases the volumetric heat treatment of coatings is undesirable, since it deteriorates their physical and mechanical properties [1].

Required compaction of coatings can be achieved using chromium and aluminum-containing phosphate binders as well as polymeric and other materials [2-3]. For the same purposes, chemical heat treatment (CHT) is used. Nitriding and carbiding of coatings are carried out in molten salts or gaseous media, while boriding and siliciding – in various plasters [4]. When the temperature of such processes is low (usually below 600°C), CHT can affect the adhesion strength of coatings mainly due to partial relaxation of stresses in the coating.

In order to increase the coating density, methods of subsequent processing of coatings have become widespread such as overflow in a furnace or with an open flame of a gas burner, as well as impregnation with plastics or molten metals.

The current methods of coating processing have a number of disadvantages: as a rule, during the overflow the pores are closed only at the outer surface of the coating while in the subsurface layers they preserve. Similar effect is provided by filling them with molten metal or plastic mass: no through filling of the pores occurs. The above picture leads to the fact that during the operation of gas-thermal coatings under the conditions of contact interactions in the process of wear, the pores become open. Thus, there appear channels through which the chemically active medium directly flows to the steel base surface. Ultimately, the processes of local corrosion damage are actively developing up to the part failure.

An increase in the density of the sprayed coatings is facilitated by an increase in the intensity of the mechanical-thermal interaction between particles of the powder and the base during both formation of coatings and subsequent mechanical-thermal treatment. The use of mechanical-thermal treatment of as-formed coatings (for example, deposited by gas thermal spraying) makes it possible to increase the coating density in parallel with maximal preservation of the original structure and properties of the powder [5].

To obtain coatings with low residual porosity, various procedures are widely used, including hot processing of powder layers by pressure.

In order to improve the quality of gas thermal coatings, the mechanic-thermal formation (MTF) of porous layers has been used immediately after deposition. As a result, the density of the coatings increased significantly and the porosity decreased (Table 1) [1].

A significant decrease in porosity after MTF in comparison with the effect of gas-flame treatment is due to the positive role of the mechanical factor, which under high temperatures determines the development of plastic deformations that contribute to the "healing" of pores [1].

The interaction of materials in the solid phase is activated not only by temperature, but also by pressure [6]. Herein, for its marked acceleration at high temperatures, rather low pressures are required to initiate the directed motion of structural defects [7, 8].

Table 1

Effect of subsequent treatment on porosity of coatings

Material of coating	Initial porosity, %	Porosity after treatment, %	
		Melting with a gas burner	MTF (Electric contact treatment)
BrAZh9-4	18	2	0.07
SNGN-35	7	1.30	0.10
3V16K	6	1.45	0.08
VK-52	8	1.35	0.07

Hence, the use of MTF is a more effective method of increasing the density of coatings than heat treatment. It can be carried out in the same technological chain with the coating deposition, just along the layer of as-formed coating by rolling in rolls, rollers [7], using heating with the flame of an additional burner.

According to the reviewed literature and patent information, among the large number of current mechanic-thermal methods of hardening parts with powder and compact materials, the advantage should be given to electric contact ones [8-11], because they allow one: to obtain practically non-porous coatings; more than 150 MPa; to preserve the original properties of the coating materials, to improve the properties of the base material, to achieve the minimum zone of thermal influence of current on the part (0.1 ... 0.3 mm) thanks to the short duration of heating pulses, and to increase the thickness of coatings by 3 ... 6 times. Moreover, they are characterized by high productivity along with low energy consumption and do not require any protective atmosphere, light radiation or gas release.

The electric contact method of hardening (formation of coatings) is carried out under pressure with direct transmission of electric current [12] and refers to pulse technologies, which are based on the principles of synchronous combination of pulsed modes of mechanical and electrical energy. It is a type of hot pressing. Unlike the conventional powder metallurgy technology, a direct passage of an electric current through the contact activates and accelerates the processes that determine properties of sintered materials. Powder under the influence of electric heating becomes plastic in a short time and easily deforms. The dominant processes in the electric impulse method of forming coatings are those that occur during both hot pressing and pressure welding. The degree of participation of either of the processes is different and depends on temperature, pressure, and material properties.

The purpose of the study

In order to confirm the efficiency of the electric contact method for forming powder coatings (electric contact processing) with reduced porosity, the task was set: to investigate the relationship between the elastic modulus and the porosity of powder coatings.

Investigation of dependence of the elastic modulus on the porosity of powder coatings in the electric contact method

In practice, porosity is most often determined by the planimetric method of metallographic analysis. The measurement of the elastic modulus of materials is performed by both dynamic and static methods [13]. Analysis of the literature data on the elastic characteristics of coatings showed that the ratio of the values of the dynamic and static moduli can vary in a wide range: from 1 to 10 [13]. Taking into account that the method for determining the adhesion and cohesive strength of the coating assumes the statistical application of tensile forces, it is obvious that the use of the elastic modulus measured under applied load will make it possible to more objectively evaluate the stress-strain state of the coating and, consequently, its limit characteristics.

In paper [14], dependence of the elastic modulus on the porosity has been shown. The first was determined by calculation using the Kashin procedure [15]. A steel base was chosen as an object of research for glass-ceramic and cermet coatings. The value of the elastic modulus for a monolithic material was higher ($7.8.10^4$ MPa) than for a porous one ($6.2.10^4$ MPa) at a porosity of 10% and (7.10^4 MPa) at a porosity of 5%. The elastic modulus of cermet coatings with a porosity of 5% was $21.5.10^4$ MPa, which is 20% higher than that of the corresponding steel coatings (18.10^4 MPa).

It has been noted [16] that porosity of ceramic coatings exhibits the strongest effect on the elastic modulus. For inorganic glasses, the experimental results are presented in the form of the dependence [17]:

$$E = E_0(1-\alpha_E P)\,, \tag{1}$$

where E is the elastic modulus;
E_0 is the elastic modulus of non-porous material;
α_E is a constant obtained by calculation for spherical closed porosity;
P is the porosity.

The literature review has shown that there are predominantly data on the dependence of the elastic modulus on porosity for compact materials, but not for coatings. In particular, for sprayed zirconium boride-copper coatings no relationship between the elastic modulus and the density of the thermal gas coating was found [16]. Most researchers consider porosity and elastic modulus as independent characteristics, and thus do not establish any relationship between them. From the experimental results [17] follows a stable dependence of the elastic modulus on porosity, close to a linear one, for glass-0ceramic coatings on austenitic steel Kh18N10T.

In order to reveal elastic modulus-porosity relationship for sprayed coatings in the case of electric contact hardening, we used standard samples.

The values of the modulus of elasticity for samples with porosity from 0 to 30% were obtained by calculation according to the method described in [18], where the dependence of the physical and mechanical properties of compact materials on porosity has been studied. A number of properties was shown to decrease monotonically with increasing porosity and to be described by a generalized function:

$$æ = æ_0\,(1 - P)^{m,} \tag{2}$$

where æ is a numerical characteristic of properties for a porous body;
$æ_0$ is the same for a non-porous body;
P is the porosity, fractions of units; m is a constant exponent.

Yu. Kharlamov [19] has developed a volumetric model of a thermal gas coating in the form of monolayers of cylindrical monoparticles:

$$æ = æ_0\, f\,(F)\,, \tag{3}$$

where F is the shape factor for particles forming the coating, which serves as a criterion for the relationship of the porosity with the relative adhesive and cohesive bond strength.

In general, the distribution of the E_0 values is close to normal. The most probable value is E_P = 2.104 MPa with a standard deviation of $0.86.10^4$ MPa. For compact zinc E = 9.10^4 MPa [19]. The decrease in the elastic modulus for a coating obtained by electric arc spraying may be due to the presence of 20% pores and its layered structure (Table 2, Fig. 2). Coating material: powder of hard alloy PG-12N-01 (base Ni, 8 ... 14% Cr, 1.7 ... 2.5 V; 1.2 ... 3.2 Si; 1.2 ... 3.2 Fe; 0.3 ... 0.6 C); flux-cored wire PP FMI-2; charge FKhB (50% Cr; 20% B, 7% Al, 3% Ti, 20% Fe) + Al.

Table 2

Dependence of mechanical properties of coatings (in particular, elastic modulus) on porosity

Method	Material	Elastic modulus E·10^{-5}, MPa						
		Base Steel 45	Porosity of coating, %					
			5	10	15	20	25	30
Gas flame spraying	PG-12N-01	2	-	-	3.2	2.7	2.5	2.2
Electric arc spraying	PP FMI-2	2	-	-	0.8	0.75	0.70	0.60
Electric contact	PP FMI-2	2	1.35	-	-	-	-	-

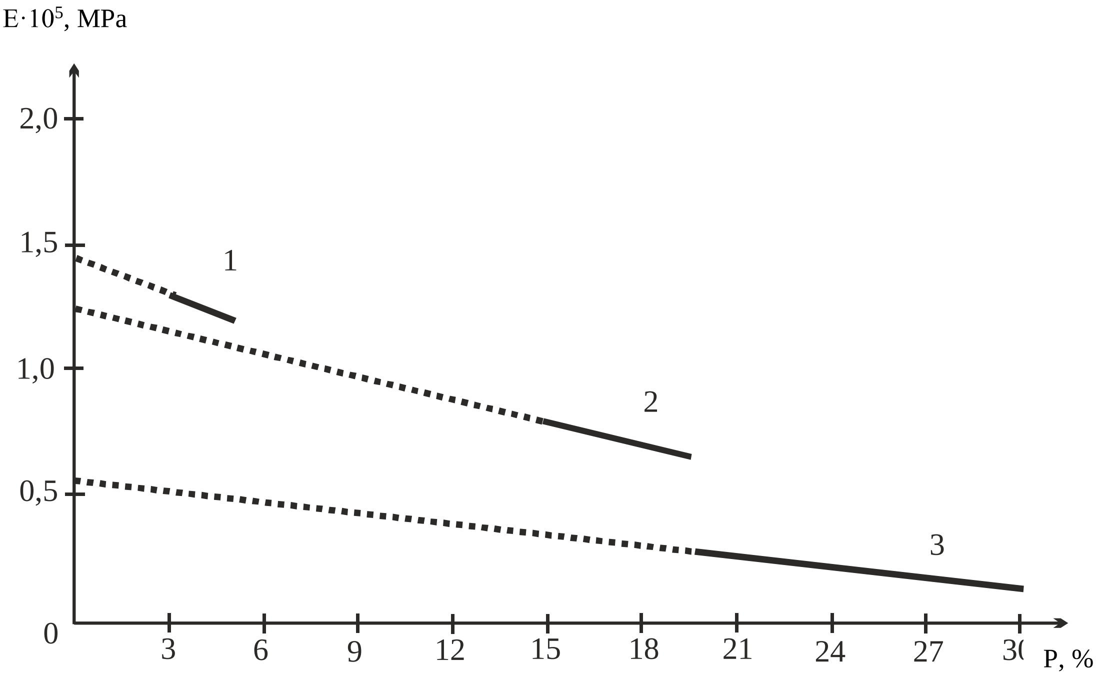

Fig. 1. Relationship between porosity and elastic modulus of coatings: 1 – coating obtained by the electric contact method; 2 – coating obtained by electric arc spraying; 3 – coating obtained by the gas flame method

Conditions of the electric contact method for forming coatings: voltage 3 ... 6 V; current 8 ... 12 kA; load on the electrode 10 ... 30 MPa; current pulse time 0.02 ... 0.04 s; pause time 0.02 ... 0.04 s.

Conditions of the electric arc spraying: voltage 18 ... 35 V; current 50 ... 600 A; the nozzle-surface distance 50 ... 200 mm; compressed air pressure 0.4 ... 0.5 MPa; compressed gas (air) consumption 60 ... 150 m^3/h.

Conclusions

The decrease in the elastic modulus of coatings is due to the presence of porosity (up to 30% after gas flame spraying and up to 20% after electric arc spraying). The electric contact method of forming coatings (electric contact method of processing coatings) makes it possible to reduce the porosity to 5-6% and to bring the value of the elastic modulus closer to that of compact materials.

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Лопата А.В., Смирнов І.В., Зіньківський А.П., Лопата Л.А. Залежність модуля пружності порошкових покриттів від їх пористості при електроконтактному методі

Досліджено зв'язок між модулем пружності та пористістю порошкових покриттів при різних методах їх нанесення. Пористість є основним засобом оцінки якості покриттів та залежить від технології їх отримання. Зниження модуля пружності покриттів при газополум'яному напиленні обумовлено наявністю пористості до 30%, а при електродуговому напиленні – до 20%. Електроконтактне припікання покриття дозволяє знизити пористість до 5-6% і наблизити значення модуля пружності покриттів до модуля пружності компактних матеріалів.

Ключові слова: електроконтактний метод формування покриттів, порошкові покриття, пористість модуль пружності, механічні властивості, адгезійна міцність

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Investigation of the process of surfacing and vibration deformation during the restoration of plowshares and discs of tillage machines

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Abstract

The analysis of ploughshare wear is given in the article and the characteristic requirements to the technological process of restoration of their worn surfaces are established. The choice of restoration technology was justified taking into account the nature of defects and the degree of wear of the working surfaces of cutting elements, their material, hardness, design parameters, accuracy of processing and cost of repairs. Quantitative and qualitative assessment of the reliability of the cutting elements of the plowshares of tillage machines, restored by different methods, was carried out by comparison with the same indicators of the new ones. Analysis of the condition of restored and new plowshares was carried out on their wear in the process of laboratory and operational tests. Laboratory researches on strengthening of plowshares by a method of vibration deformation were carried out on the specially made installation consisting of the following main knots: vibroexciter IV-105 with adjustable unbalance; hydraulic lifting systems; auxiliary equipment. The deformation rate was regulated by a V-belt double-circuit variator of the pump drive. To study the effect of normal and vibration load on the strength characteristics of the processed material, the study was performed on samples-models, and then - on the details. The samples were new plowshares, experimental studies on which provided the identity of the nature of the course of wear of their cutting elements. It is experimentally established that the hardness of the material on the surface of the blade, depending on the technological process of restoration was: restored by welding tires of steel 45 with surmaite surfacing and vibration hardening - 71-74 HRC; new plowshares made of L-53 steel, subjected to vibration hardening 66-68 HRC; new from 65G steel and strengthened by vibration deformation 57-59 HRC.

Key words: surfacing, vibration deformation, wear resistance, tillage machines, ploughshare restoration, disk hardening, durability, sormite.

Introduction

The operation of plow plows on sandy, loamy and loamy soils is associated with intensive wear of the working bodies, which leads to limited failure. The most significant defect is the wear of the ploughshare sock, which has a radial shape, the recurrence coefficient of which is 0.84; while 30% of the parts retain a geometric shape that satisfies the technical conditions. Meanwhile, technological processes to eliminate this defect are ineffective. Therefore, it is necessary to conduct research aimed at developing methods for restoring plowshares that provide increased post-repair life.

Increasing the durability of plowshares is possible with the use of technologies that combine restoration and strengthening, preventing intense abrasive wear [1].

At the same time, the use of methods of eliminating radial wear should not affect the appearance of bends, destruction, distortion, wear in other parts of the part during their further operation. It is necessary to withstand the geometry of the restored ploughshare, which meets the agronomic requirements.

Restoration is usually reduced to the deposition of wear with special electrode materials that provide sufficient wear resistance of the surface, without taking into account the possibility of other defects in the process.

Sormite surfacing and vibration hardening have wide possibilities in this respect, where the intermediate layer has increased elastic and plastic properties, in comparison with a wear-resistant surface coating.

However, research on the creation of such technologies in relation to the working bodies of tillage machines is not enough, so the work is relevant.

Literature review

Restoration of worn parts allows you to reuse, sometimes reuse depleted parts and assembly units.

Technical and economic indicators of a number of agricultural machines are still very low due to short service life and poor performance of responsible parts (especially working bodies), forced downtime with their periodic replacements, the cost of additional funds for the restoration of parts and more. Tillage machines and implements suffer the most from such shortcomings, they perform a very large amount of work in agricultural production [2].

Rapid wear of plowshares, cultivator tines and other tillage machines and implements prevent the increase of labor productivity in agriculture.

The working bodies of plows include a ploughshare, a dump, a disk knife and a field board. The ploughshare is intended for cutting of a soil layer from below and together with a dump of its separation from the party (from a furrow wall). There are trapezoidal and chisel-shaped plowshares. They are made of special ploughshare steel L-53 or L-56. The lower part (blade) with a width of 50…60 mm is hardened to a hardness of HB 444 ... 500 [3].

The working bodies of cultivators include paws. Depending on the purpose, they are divided into the following types: floor or flat-cut (one-sided or arrow); universal (arrow-shaped), designed for pruning weeds and crushing the soil; loosening - chisel-shaped, reversible and spear-shaped. On soils prone to wind erosion, cultivators are used - cultivators-deep cultivators, the working body of which is a ploughshare [4].

Wear of plowshares, cultivator paws, knives and other cutting parts is manifested mainly in the deterioration of agronomic and to a lesser extent energy performance.

Worn-out working bodies of tillage machines (plowshares, cultivator paws, flat cutters knives) are characterized by blunting and change of the basic sizes: thickness of a blade, width of an occipital chamfer. The ploughshare in the process of work forms an occipital chamfer with a width S at an angle α to the loose soil layer [5].

When defecting plowshares and cultivator paws, you can use three ways to detect defects [6]:

- external inspection (obvious defects are revealed - breakages, cracks, chips);
- knocking (reveal hidden defects, weakening of bolts, rivets, cracks, etc.);
- measurement of wear is determined by universal means (calipers) and templates.

Improving the quality of machine repair while reducing its cost is the main problem of repair production. In the structure of the cost of overhaul of machines 60… 70% of the costs are the purchase of spare parts, which in market conditions remain in short supply in the event of rising prices. The main way to reduce the cost of repairing machines - reducing the cost of spare parts. This can be achieved in part through careful and competent disassembly of parts. However, the main reserve is the restoration and reuse of worn parts, as the cost of restoring most parts is usually absorbed in 20… 60% of the price of new parts [7].

The blades of the ploughshare are sharpened when blunting the working side to a thickness of 1 ... 1.5 mm with a chamfer width of 5 ... 7 mm and sharpening angles of 25 ... 40 °. After wear to a width of less than 108 mm (check the template), the ploughshare is restored by forging to a normal profile (with a deviation in width of not more than 5 mm and a length of not more than 10 mm) due to the metal back (shop). Plowshares should be held no more than four times.

To delay the ploughshare is heated in furnaces or a blacksmith's furnace to a temperature of 900 ... 1200 ° C along its entire length and pulled on a pneumatic hammer. The surface of the extended ploughshare should be smooth, without cracks. Deviation of its back from flatness is allowed a little more than 2 mm, blades (convexity of a working surface) - to 4 mm.

After stretching the ploughshare is sharpened on the front side, then heated to 700 ... 820 ° C and hardened along its entire length to a width of 20 ... 45 mm in salt water at a temperature of 40 ° C (time 5 ... 6 s) on the side blades to a hardness of 444 ... 650 HB. Then released while heating to 350 ° C with air cooling.

More effective isothermal hardening, when the ploughshare is heated to a temperature of 880 ... 920 ° C and the blade is cooled to 350 ° C for 3.0 ... 3.5 s in heated to 30 ... 40 ° C 10% saline water. After that it is cooled in air. To increase the wear resistance of the ploughshare blade is made self-sharpening by surfacing its back side with a hard alloy. Before surfacing, a strip 25 ... 30 mm wide is pulled from the ploughshare on the blade side and a section 55 ... 65 mm wide is pulled into the sock of the chisel-shaped ploughshare.

The thickness of the surfacing layer should be 1.4-2.0 mm. Surfacing is carried out on the installation of HDTV alloy sormite № 1, acetylene-oxygen flame with a rod 0 6 mm from sormite № 1, electrodes brand T-590 and powder darts. When worn to a width of less than 92 mm, the ploughshare is restored by welding the strip, making it also self-sharpening.

Crushing of the knife blade is allowed in no more than three places up to 1.5 ... 2.0 mm deep and up to 15 mm long. Disc warping is allowed a little more than 3 mm. Damaged discs are ruled on the stove in a cold state. They are sharpened to a blade thickness of 0.5 mm on the installation OP-6112 for sharpening disc knives and on devices for the lathe cutters with plates of hard alloys T15K6 and others. Axial and radial beating of the disk is allowed no more than 3 mm.

Collection control. The plow after repair in the unit with a tractor is established for check on the control stand platform. It is made on a reinforced concrete base with a variable (for different tractors) track of channels with stops for the tractor and the control plate with a stencil, which marks the position of the working bodies, wheel supports and other control points of the plow. The completeness of the plow, the correct installation of its working bodies, the rigidity of fastening parts and other parameters are checked on the stand-platform.

When working in a properly assembled plow, the plowshares, the ends of the field boards, the heel of the rear field board, the furrow and the rear wheels must lie in the same plane. Deviations from the parallel field edges of dumps and plowshares are allowed only in the direction of the furrow, but not more than 10 mm. Socks and heels must lie on one straight line with a deviation of not more than ± 5 mm.

The distance between the inner edge of the furrow wheel and the heel of the ploughshare of the first case is allowed 50 ± 5 mm. Displacement of the rear wheel from the straight line passing through the field edge of the ploughshare of the last case is allowed a little more than 5 mm. The plane of the rear wheel disc must have an inclination of 6 ... 10 ° from the vertical towards the plowed field. The clearance between the heel heel or the rear edge of the field board and the plane of the control plate is allowed up to 10 mm.

The location of the plow sock above the heel or field board is not allowed. The blade and the ploughshare must fit snugly together, and the ploughshare must protrude no more than 1 mm above the blade surface at the joint. It is not allowed for the surface and the field edge of the blade to protrude above the surface and the edge of the ploughshare. The screw mechanisms of the plow must rotate freely if the steering wheel is applied with a force of not more than 150 ... 200 N.

The technology of repair of mounted and trailed plows is similar. Repaired plows for long-term storage paint, which work surfaces are covered with anti-corrosion composition.

The development and application of alternative energy-saving and efficient methods of ensuring the reliability of tillage implements by strengthening their surface treatment is relevant. An effective method is the technology of restoration and strengthening of the working bodies of tillage machines by means of vibration.

In this regard, research is particularly relevant to determine the technological parameters of the most responsible working bodies of tillage machines in their production and restoration, aimed at improving the reliability and durability. Therefore, the creation of technology for strengthening such bodies with the use of mechanical vibrations can be considered one of the important scientific, applied and promising tasks for the development of the agro-industrial complex of Ukraine.

Purpose

The purpose of the research is to increase the reliability of ploughshare working bodies of tillage machines by restoring them by the method of vibration hardening.

Research methodology

To study the effect of normal and vibration load on the strength characteristics of the processed material, the study was performed on samples-models, and then - on the details. The samples were new plowshares, experimental studies on which provided the identity of the nature of the course of wear of their cutting elements.

The thickness of the blade samples - plowshares during the tests varied within 2.0 ± 0.5 mm, the sharpening angle was 25 °, 30 ° and 35 °. The amplitude of oscillations of the processing tool was 0.25 - 0.75 mm, the frequency of oscillations 700 - 2100 min-1, hardening time - 10 - 30 s.

The levels of factors of the multifactorial experiment were determined by previous experimental studies [8].

Determination of stresses in the material of the samples, processing effort, the amount of deformation was performed by strain gauge using an oscilloscope, amplifier TUP-12, strain gauges type PD-5-200.

Studies of the microstructure were performed using a microscope MIM-8, hardness tester TK-2M, microhardness tester PMT-ZM; measurement of surface roughness of samples and parts was performed on a profilometer mod. 253 and profilographs of fashions 252.

Evaluation of changes in the macrostructure of the ploughshare blade along its generator was performed using the planimetric method, and evaluation of their reliability was determined by the probability of trouble-free operation, provided that the blade parameters do not exceed the limits.

The reliability of the results of experimental studies was evaluated in accordance with the accepted theoretical law of distribution, with a given value of confidence probability $\alpha = 0.95$.

Experimental studies of the wear resistance of plowshares, restored by various methods, were carried out on the stand - the soil channel, which adhered to the conditions of similarity of plowshares on the stand and during operation, ie preserved the nature of wear. The humidity of the working mixture (10-18%) was controlled using a moisture meter EV-2.

Experimental tests were the final stage of research to determine the effectiveness of various methods of restoring the plowshares of tillage machines. Plowshares were tested in four versions: new steel 65G; restored by welding tires made of steel 45 with sormite surfacing and vibration hardening; new steel L-53, subjected to vibration hardening; new steel 65G, subjected to vibration hardening.

Tests of these variants of plowshares allowed to estimate their operational reliability.

Research results

The change in the shape of the ploughshare blade from technological (initial) to working (worn) occurs as a result of the action of forces on it, in its various planes (Fig. 1):

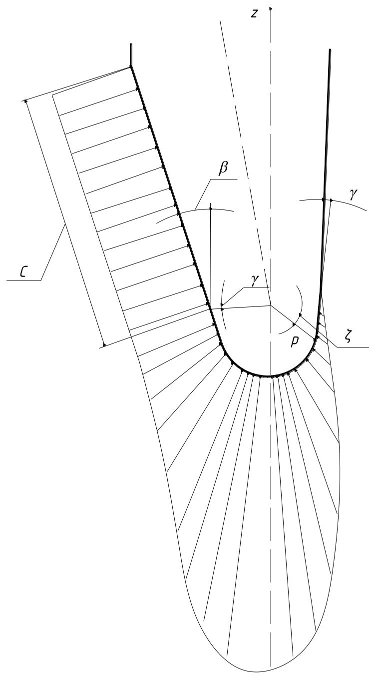

Fig. 1. Scheme of stress distribution in the cutting part of the ploughshare

The nature of the change in the force on the blade depending on the sharpening angle β is shown in Fig. 2.

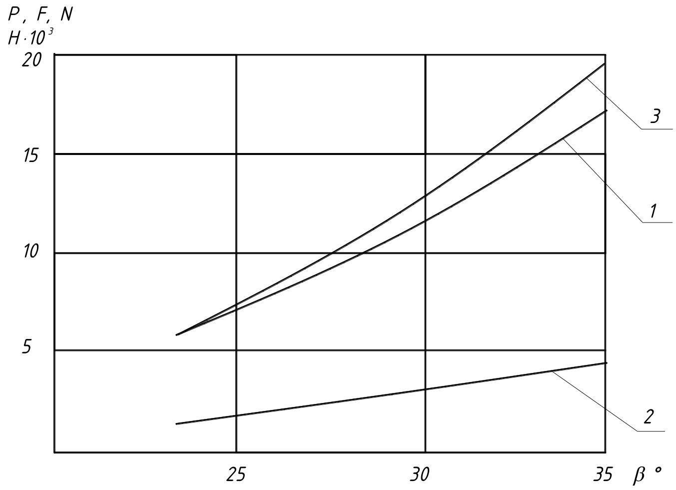

Fig. 2. Curves of changes of efforts on a blade depending on a sharpening angle:
1 - normal component of the cutting force; 2 - component directed along the generative; 3 - total cutting force

It was found that increasing the sharpening angle β from 30 ° to 35 ° causes an increase in mainly normal N and total P cutting force of 1.49 and 1.51 times, respectively.

It has been experimentally established that the criteria for the limiting state of plowshares can be considered as the wear values of the sock Δh and the thickness of the ploughshare wall. The amount of wear of the sock in plowshares, restored by welding tires made of steel 45 with sormite surfacing and vibration hardening, respectively, 1.2 and 1.1 times less than in plowshares made of steel L-53 and steel 65G, subjected to vibration hardening. Wear on the wall thickness of plowshares, restored by welding tires made of steel 45 with surmaite surfacing and vibration hardening, respectively, 1.54 and 1.2 times less compared to the wear of plowshares made of steel L-53 and steel 65G subjected to vibration hardening [9].

Based on the obtained equations for plowshares, restored by welding tires made of steel 45 with sormite surfacing, the surface dependence of the wear of the ploughshare blade thickness on the frequency and amplitude of oscillations of the working tool at a processing time of 20 s.

As a result of the analysis of regression equations it can be stated that to increase the wear resistance of renewable plowshares vibration hardening should be carried out at an oscillation frequency of 1400 min-1, oscillation amplitude of 0.5 mm and hardening time of 20 s.

Studies of the microstructure of deformed specimens have shown that during vibrational deformation it is more fine-grained and uniform to a metal depth of 180-320 μm, which creates conditions that contribute to the strengthening of the treated surface (Fig. 3).

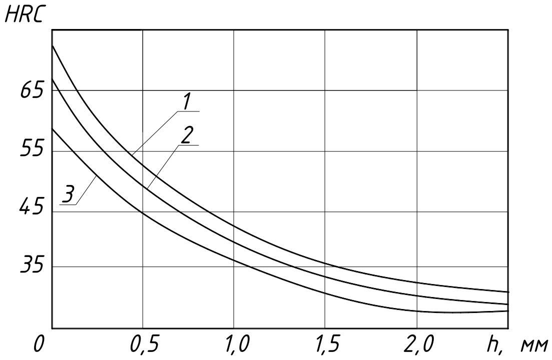

Fig. 3. Changes in the hardness of the depth of the plowshares depending from the recovery method: 1 - restored by welding tires made of steel 45 with sormite surfacing and vibration hardening, 2 - new plowshares made of L-53 steel subjected to vibration hardening, 3 - new plowshares made of steel 65G, strengthened by vibration deformation

It is experimentally established that the hardness of the material on the surface of the blade, depending on the technological process of recovery was: restored by welding tires of steel 45 with surfacing and vibration hardening - 71-74 HRC; new plowshares made of L-53 steel, subjected to vibration hardening 66-68 HRC; new from 65G steel and strengthened by vibration deformation 57-59 HRC.

The hardness of the ploughshare material, restored by welding 45 steel tires, surfacing and vibration hardening, is 1.23-1.35 times higher than the hardness of the 65G steel ploughshare material without hardening.

Studies have shown that during the restoration of plow plowshares by various methods in their material arise and redistribute significant residual stresses due to thermal effects on the parent metal during surfacing and various methods of hardening [10].

Compressive stresses increase as the layers are removed inwards and when strengthened with the amplitude of the machining tool A = 0.5 mm was at a depth of 0.08 - 0.15 mm: MPa; at strengthening of plowshares from steel L-53 and steel 65G accordingly 375 - 385 MPas and 420 - 435 MPas. At a depth of 0.22 - 0.32 mm, they turn into tensile stresses and at a depth of 0.40 - 0.48 mm, respectively, were: 460 - 470 MPa; 485 - 500 MPa; 530 - 540 MPa.

According to the obtained values of strain gauges, curves of changes of residual stresses along the depth of the ploughshare blade material are constructed (Fig. 4).

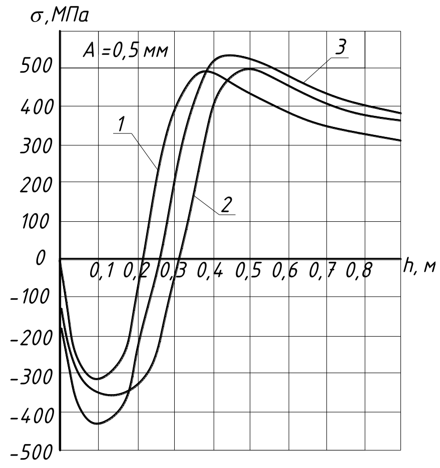

Fig. 4. Changes in residual stresses in depth depending on the method of plowing recovery, amplitude of oscillations of the processing tool and processing time t = 20 s: 1 - restored welded tires of steel 45 with surmaite surfacing and vibration hardening, 2 - new plowshares of steel L-53 subjected to vibration deformation, 3 - new plowshares made of steel 65G, strengthened by vibration deformation

Studies of the process of wear dynamics of cutting elements were carried out for plowshares: restored by welding tires made of steel 45 with surmite surfacing and vibration hardening; new plowshares made of L-53 steel, subjected to vibration deformation; new 65G steel plowshares reinforced by vibration deformation; new plowshares from steel 65G. The depth of the plowshares was 22-27 cm, and the speed was 1.4 m / s.

The wear intensity of the cutting edge thickness of plowshares, restored by welding tires made of 45 steel with surmite surfacing and vibration hardening, is 1.17 times less than that of new 65G steel plowshares. The change in the amount of blunting of the blades of plowshares made of 65G steel subjected to vibration hardening is 2.06 less compared to the new ones made of 65G steel without hardening [11].

The conducted bench tests allowed to determine the nature of the change in the shape of the ploughshare and the thickness of its cutting edge, as well as to choose a more efficient technological process of its restoration. Analysis of the obtained data allowed us to conclude that the wear resistance of the ploughshare depends largely on the type of processing during recovery, as well as on the combination of base and weld material.

As a result of bench tests the variant of restoration of a ploughshare by welding of tires from steel 45 with automatic surfacing of sormite and the subsequent vibration strengthening is offered. A lower rate of blade thickness reduction of 0.003 mm / ha compared to other variants was set.

The reliability of these plowshares was evaluated by the time of operation of the plow unit per unit of wear width, toe and thickness of the plow. The highest values of these parameters are 38.07 ha / mm; 8.13 ha / mm and 56.9 ha / mm had plowshares, restored according to the developed technology, and the smallest 31.24 ha / mm; 7.08 ha / mm and 46.67 ha / mm are the new 65G plowshares [12].

No plow failures were observed during operation.

These changes in the geometry parameters of plowshares and their wear were removed every 50 ha of work.

Operational studies of these variants of plowshares have confirmed full compliance with bench tests. More reliable are the plowshares restored by welding of tires from steel 45 with sormitic surfacing and vibration strengthening: speed of wear of width, a sock and plow thickness accordingly 1,29; 1.17 and 1.22 times less than the new 65G steel [13]. The average wear of these parameters was 9.56 mm, 43.20 mm, 6.56 mm, respectively (Fig. 5).

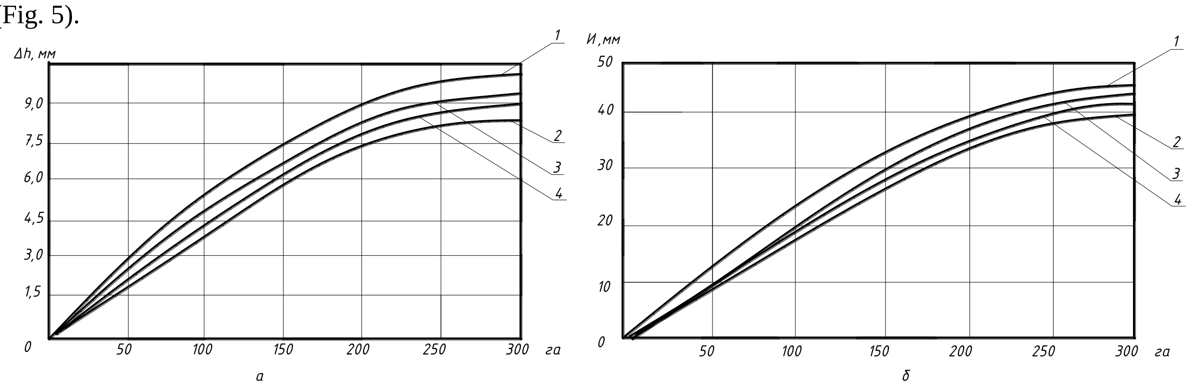

Fig. 5. Changes in wear of width (a) and sock (b) of a plow ploughshare depending on the operating time: 1 - new plowshares made of 65G steel, 2 - restored by welding tires made of steel 45 with sormite surfacing and vibration hardening, 3 - new plowshares made of L-53 steel, subjected to vibration hardening; 4 - new plowshares made of 65G steel, subjected to vibration hardening

An assessment of the reliability of tillage machines working with these working bodies, their performance and the coefficient of technical use [14].

It was found that the highest value of KTV = 0.992 were plow units working with plowshares, restored by welding tires made of steel 45 with sormite surfacing and vibration hardening, and the lowest KTV = 0.948 - with new plowshares made of steel 65G. The coefficient of technical use of plow units with plowshares, restored by the developed technology, is 1.05 times higher than that of plow units with new plowshares made of 65G steel.

Conclusions

It is established that during vibrational deformation a larger fine-grained and uniform metal microstructure is formed at a depth of 180-320 μm, conditions are created that ensure the accumulation of residual deformation and strengthening of the working layer of plowshares. Regularities of structure formation of the working layer within the limits of vibration processing parameters are revealed.

The hardness of the ploughshare material restored by welding 45 steel tires, grade surfacing and vibration hardening is 1.23-1.35 higher than the hardness of 65G steel ploughshare materials without hardening.

A computational-experimental method for determining the reliability of plow plowshares according to the main criteria, based on the use of measurement results obtained in the conditions of bench and operational tests, has been developed.

In plowshares, restored by welding tires made of steel 45 with automatic surfacing and vibration hardening, wear rate of width, sock and plow thickness in accordance with 1.29; 1.17 and 1.22 times less than the new 65G steel.

The estimation of reliability of plow plowshares of substantiation of processing machines for the coefficient of technical use is executed.

It is established that the coefficient of technical use of the plow unit with plowshares, restored by the developed technology in comparison with the new ones by 105 times.

The reliability of the plowshares of these options was evaluated by the operating time of the plow unit, which is per unit of wear width, toe and thickness of the plow. The highest value of these parameters is 38.07 ha / mm; 8.13 ha / mm and 56.9 ha / mm of small plowshares, restored according to the developed technology, and the smallest 31.24 ha / mm; 7.08 ha / mm and 46.67 ha / mm - new 65G steel plowshares.

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Марченко Д.Д., Матвєєва К.С. Дослідження процесу наплавлення і вібраційного деформування при відновленні лемешів і дисків ґрунтообробних машин.

В статті приведено аналіз зносу лемешів і встановлено характерні вимоги до технологічного процесу відновлення їх зношених поверхонь. Вибір технології відновлення обґрунтували з урахуванням характеру дефектів і ступеню зносу робочих поверхонь ріжучих елементів, їх матеріалу, твердості, конструктивних параметрів, точності обробки і собівартості ремонтних робіт. Кількісну та якісну оцінку надійності ріжучих елементів лемешів ґрунтообробних машин, відновлених різними методами, проводили порівнянням з такими ж показниками нових. Аналіз стану відновлених і нових лемешів проводили по їхньому зносу в процесі проведення лабораторних і експлуатаційних випробувань. Лабораторні дослідження по зміцненню лемешів методом вібраційного деформування проводили на спеціально виготовленій установці, що складається з наступних основних вузлів: віброзбудника ІВ-105 з регульованим дебалансом; системи гідравлічного підйому; допоміжного обладнання. Швидкість деформування регулювали клинопасовим двоконтурним варіатором привода насоса. Для вивчення впливу звичайного і вібраційного виду навантаження на міцнісні характеристики оброблюваного матеріалу дослідженя проводили на зразках-моделях, а потім - на деталях. Зразками слугували нові лемеші, експериментальні дослідження на яких забезпечували ідентичність характеру протікання зношування їх ріжучих елементів. Експериментально встановлено, що твердість матеріалу на поверхні леза в залежності від технологічного процесу відновлення склала: відновлених приваркою шин зі сталі 45 з наплавленням сормайтом і вібраційним зміцненням - 71-74 HRC; нових лемешів зі сталі Л-53, підданих вібраційному зміцненню 66-68 HRC; нових зі сталі 65Г і зміцнених вібраційним деформуванням 57- 59 HRC.

Ключові слова: наплавлення, вібраційне деформування, зносостійкість, грунтообробні машини, відновлення лемеша, зміцнення диска, довговічність, сормайт

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Heat and mass transfer models at boundary lubrication to determine the transition temperatures

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Abstract

At present, kinetic and thermodynamic methods for assessing the lubricating effect of oils are being increasingly developed. At the limit friction, the reduction of friction and wear of surfaces is due to the ability of the lubricant to form layers of adsorption or chemical origin on the surface. Analytical models of transition temperatures and wear in the limit lubrication mode must be used to mathematically describe the processes in the subsystems and the transition between them. The Fourier equation of thermal conductivity is accepted as the basic calculated dependence. It is assumed that the process of heat propagation under the conditions of formation of lubricating films is not Markovian, i.e. the magnitude of the heat flux is determined by the entire "history" of heat transfer in a certain elementary volume. The equation of motion of a lubricating film over the surface of a body that is being lubricated is obtained from the equation of motion for a Newtonian continuous medium. As a result, nonlinear heat and mass transfer models are obtained to determine the transition temperatures in the formation of boundary lubricating films in the concept of structural-thermodynamic approaches to describe the processes of boundary lubrication of surfaces.

Key words: maximum lubrication, transition temperatures, mathematical model.

Introduction

At ultimate friction, the reduction of friction and wear of surfaces is due to the ability of the lubricant to form layers of adsorption or chemical origin on the surface. At the first stage (fig.1) of interaction of the surface and the lubricant, the adsorbed layer is formed by molecules of the surfactant component. Adsorbed films under certain conditions have the ability to self-organize, ie there is a process of dynamic equilibrium between the formation and destruction of adsorbed layers under the action of external factors. When the value of the first transition temperature is reached, the dynamic equilibrium is disturbed and the adsorption layers are destroyed. Most modern lubricants contain chemically active components, which at the temperature of chemical modification form chemically modified films on the metal surface, which leads to reduced friction and wear. Further increase of external influence leads to complete destruction of the boundary lubricating layer at the second critical temperature.

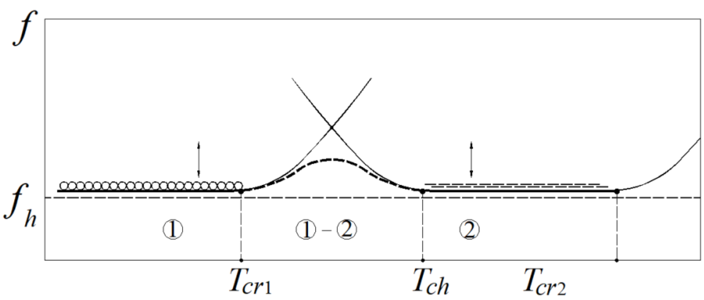

Fig.1. The kinetics of the formation of transition temperatures.

Analytical models of transition temperatures and wear in the limit lubrication mode must be used to mathematically describe the processes in the subsystems and the transition between them.

Literatuter review

Much attention is currently being paid to the study of models of heat and mass transfer during boundary lubrication. The heat transfer phenomenon is beneficial and applicable in engineering, industries, and technological processes. The production of energy with the help of some cheap resources plays a pivotal and renewable role in the industrial development of the countries. In study [1] proposes a torque calculation model that incorporates the boundary conditions of the lubricant flow field and variation of oil film temperature. The torque transfer equation of a multi-plate clutch as related to viscosity was derived by combining the three-dimensional Navier-Stokes equation with the boundary conditions of the lubricant flow field. Taking the vehicle transfer case as an example, the equation for the variation in oil film radial temperature was obtained through the thermodynamic model of a flow field. By applying the parameters derived from the temperature equation to the PWA torque transfer model, the values under four working conditions were calculated. The results show that the relative errors between the corrected torque value and the test value under the four working conditions were less than 10%. Comparative analysis of simulation and experiment shows that PWA has advantages. In paper [2] the owing to such a significant performance of heat transfer, the steady slip flow and heat transfer of tangent hyperbolic fluid over a lubricating surface of the stretchable rotatory disk is investigated. The governing nonlinear partial differential equations (PDEs) have been converted into ordinary differential equations (ODEs), which are solved numerically using the Keller-box method. The upshots of pertinent parameters upon the dimensionless distributions of velocity and temperature are deliberated. The surface drag forces and heat transfer rates are computed, and the effects of governing parameters on them are examined. In [3] the lubrication of the piston skirt-cylinder interface involves multiple physical fields, and these physical fields are coupled. A new method is proposed in this study for modeling and analysis of the lubricated piston skirt-liner interface with multi-physics coupling. The results indicate that although a thinner skirt will affect the stability of piston motion and increase the slapping noise and wear, it will benefit hydrodynamic lubrication between skirt and cylinder and reduce friction power loss. In study [4] the influence of two thermal effects in a low-speed two-stroke diesel engine on piston ring lubrication performance are discussed in detail. For the TDCL, a steady-state heat-transfer model based on sequential fluid–solid coupling is used to solve for the heat-transfer coefficient and temperature on the coupling surface between the cylinder liner and the cooling water jacket. The boundary condition used to calculate the TDCL is the temperature distribution on the inner surface of the cylinder liner calculated empirically and verified experimentally. The results of the TDCL and the ASTM model are used in the lubrication model to analyze how the thermal effects influence the lubrication performance of the piston-ring–liner tribological pair. A fluid-structure coupling numerical model of an oil-jet lubricated cylindrical roller bearing (CRB) in a high-power gearbox is developed, in which the volume of fluid (VOF) method and slip mesh model are used. The heat sources of bearing are defined as the transient thermal boundary in [5]. The differences of temperatures between the rigid and flexible bearings are compared. The simulation results are validated by the presented experimental results. It indicates that the oil flow rate, speed, waviness amplitude and order, oil viscosity and nozzle number will significantly influence the bearing's lubricating characteristics. The flexible bearing model with the transient thermal boundary is more accurate than those of other two models. To suppression the increment of bearing temperature, the waviness should be reduced. Advancements in mechanical expertise and rigorous need for gyratory components of machines expedite scientists towards essentiality of the eternal evolution of modified lubricants to corroborate the reliability, innocuous procedure and stability of sundry bearings. To enhance the performances at heftily ponderous load and high velocity, the high molecular polymers are utilized in mechanical bearings as lubricant. These lubricants [6] are non-Newtonian in characteristics and comply with different constitutive relationships. One of them is the power law lubricant which complies with Ostwald model and is broadly utilized for the engineering lubrication. The derivation of the slip-flow conditions at the interface of bulk Jeffrey fluid and the thin layer non-Newtonian lubricant is performed over a disk spiraling with simultaneous radial stretching and rotation. To obtain a homogeneous solution, the power-law index is suggested 1/3 and no-slip boundary condition is converted into an incipient slip boundary condition. A single dimensionless slip parameter is introduced to regulate the velocity slip. Flow equations are obtained, and the similarity conversion is performed to obtain ordinary differential equations. Numerical results are computed to visually perceive the effects of lubrication on the flow field by incorporating the interfacial slip conditions. The presence of the lubrication enhances the fluid velocity and plays major role in the reduction of the skin friction at disk surface. Thus, the creation of models of heat and mass transfer during boundary lubrication is a modern problem.

Main material. Models of the formation of transition temperatures during boundary lubrication

The gradient law of Fourier thermal conductivity can be used in the formation of boundary oil films:

$$q_t = -\lambda \Delta T = -\lambda g_t \,, \tag{1}$$

where q_t is the heat gradient;

$g_t = \mathrm{grad}T = \nabla T$ is the temperature gradient;

λ is the thermal conductivity, [11].

To summarize Fourier's law, the Maxwell-Cattaneo relationship:

$$q_t = -\lambda g_t - \tau_t \frac{\partial q_t}{\partial \tau_t} \,, \tag{2}$$

where τ_t is the time or period of relaxation of the temperature field.

It is established [5, 6] that the isotropic solid under the conditions of lubrication is affected by the hyperbolic equation of heat transfer:

$$\frac{\partial T}{\partial \tau} + \tau_t \frac{\partial^2 T}{\partial \tau^2} = \alpha \Delta T + \frac{\gamma_t}{\rho c_p} \,, \tag{3}$$

where ρ is the the density of the lubricating film;

c_p is the її molar heat capacity;

γ_t is the density of distribution of heat energy drains.

The solution of equation (3) with the necessary initial and boundary conditions corresponds to the propagation of the temperature field with a sharply delineated front, which propagates with velocity:

$$V_t = \sqrt{\frac{a}{\tau_t}} \,,$$

де a is the coefficient of thermal conductivity.

$$a = \frac{\lambda}{\rho c_p} \,. \tag{4}$$

Therefore, equation (3) describes the process of heat propagation with a finite velocity V_t .

However, the process of heat distribution in the formation of lubricating films is not Markov, ie the magnitude of heat flux is determined by the entire "history" of heat transfer in some elementary volume.

With this approach, the equation of the relationship between heat flux and temperature gradient will take the form

:

$$g_t = -\int_0^{\Delta T} k(\theta) g(\tau - \theta) d\theta \,, \tag{5}$$

where $k(\theta)$ is the lubrication film temperature field relaxation function;

τ, θ is the coordinates of this field.

If $g(\tau - \theta) = g(\tau)$, then equation (5) passes into (1), and:

$$\lambda = \int_0^{\Delta T} k(\theta) d\theta \,. \tag{6}$$

Assuming that the relaxation $k(\theta)$ function attenuates exponentially, ie:

$$k(\theta) = \frac{\lambda}{\tau_t} \exp\left(-\frac{\theta}{\tau_t}\right), \tag{7}$$

you can go from (5) to (2).

The heat flux q_t and internal energy e of the film, taking into account the relaxation functions, can be found as follows:

$$\begin{cases} q_t = -\int_0^{\Delta T} k(\theta) g'(\theta) d\theta; \\ e = e_0 + cT - \int_0^{\Delta T} l'(\theta) T'(\theta) d\theta, \end{cases} \tag{8}$$

Where value $g'(\theta)$ and $T'(\theta)$ determined by the ratios:

$$\begin{cases} \frac{d}{d\theta} g'(\theta) = g(\tau - \theta); \\ \frac{d}{d\theta} T'(\theta) = T(\tau - \theta) \end{cases}, \tag{9}$$

where c is the volumetric heat capacity of the oil;
$l(\theta)$ is the relaxation function of internal energy, [4, 5].
Find the time derivatives of heat flux and internal energy:

$$\begin{cases} \frac{\partial q_t}{\partial \tau} = -k(\theta) g - \int_0^{\Delta T} k'(\theta) g(\tau - \theta) d\theta; \\ \frac{\partial e}{\partial \tau} = c \frac{\partial T}{\partial \tau} + l(\theta) T + \int_0^{\Delta T} l'(\theta) T(\tau - \theta) d\theta. \end{cases} \tag{10}$$

Using the conservation equation for the internal energy in the form:

$$\frac{\partial e}{\partial \tau} = div q_t + \gamma_t, \tag{11}$$

we obtain the following integro-differential equation of heat transfer in the lubricating film, considering the lubricant an isotropic material:

$$c \frac{\partial^2 T}{\partial \tau^2} + l(\theta) \frac{\partial T}{\partial \tau} + \int_0^{\Delta T} l'(\theta) \frac{\partial T(\tau - \theta)}{\partial \tau} d\theta = k(\theta) \Delta T + \int_0^{\Delta T} k'(\theta) \Delta T(\tau - \theta) d\theta + \gamma_t . \tag{12}$$

The heat flux determined by relation (5) does not explicitly depend on the instantaneous value of the temperature gradient, but is determined by the entire "history" of heat transfer. However, in explicit form, equation (5) will have the form:

$$q_t = -k(\theta) g - \int_0^{\Delta T} k'(\theta) g(\tau - \theta) d\theta . \tag{12}$$

If we use the equation for the internal energy of the film in the form:

$$l = e_0 + l(\theta) T + \int_0^{\Delta T} l'(\theta) T(\tau - \theta) d\theta , \tag{14}$$

then equation (12) will take the form:

$$l(\theta) \frac{\partial T}{\partial \tau} + \int_0^{\Delta T} l'(\theta) \frac{\partial T(\tau - \theta)}{\partial \tau} d\theta = k(\theta) \Delta T + \int_0^{\Delta T} k'(\theta) \Delta T(\tau - \theta) d\theta + \gamma_t . \tag{15}$$

At $k(\theta)\to 0$ this equation will take the form:

$$l(\theta)\frac{\partial T}{\partial \tau}+\int_0^{\Delta T} l'(\theta)\frac{\partial T(\tau-\theta)}{\partial \tau}d\theta=\int_0^{\Delta T} k'(\theta)\Delta T(\tau-\theta)d\theta+\gamma_t \,. \quad (16)$$

Equation (16) can be represented in the form close to (12):

$$l(\theta)\frac{\partial^2 T}{\partial \tau^2}+l'(\theta)\frac{\partial T}{\partial \tau}+\int_0^{\Delta T} l''(\theta)\frac{\partial T(\tau-\theta)}{\partial \tau}d\theta=k'(\theta)\Delta T+\int_0^{\Delta T} k''(\theta)\Delta T(\tau-\theta)d\theta+\gamma_t \,. \quad (17)$$

Equation (17) can be considered a mathematical model of the phenomenon of heat transfer by the lubricating film up to the formation of its limit state at temperature T_{cr1}, determined according to [7, 8] ($T_{cr1}=\Delta T$).

The equation of motion of the lubricating film on the surface of the lubricated body is obtained from the equation of motion for the Newtonian continuous medium, [11]:

$$\frac{\partial v}{\partial \tau}+(\nabla v)v=g-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\Delta v+\frac{1}{\rho}\left(\xi+\frac{1}{3}\mu\right)\text{grad div } v \,, \quad (18)$$

where p is the contact stresses in the lubrication zone;
v is the the average speed of movement of the lubricating film on the body surface;
μ is the chemical potential of the surface, [11];
ξ is the chemical potential reduction factor.

In the case of uncompressed solid medium in the oil, when the value $\text{grad div } V$ rather small, equation (18) turns into the Navier-Stokes equation:

$$\frac{\partial v}{\partial \tau}+(\nabla v)v=g-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\Delta v \,. \quad (19)$$

In mathematical modeling of the processes of physicochemical transformations of the lubricating film until the values are reached T_{ch} i T_{cr2} we will analyze the phenomenon of mass transfer in the film itself. To do this, we use Fick's diffusion law [10, 11, 12]:

$$q=-De\Delta\rho \,, \quad (20)$$

where De is the effective diffusion coefficient;
q is the irreversible flow of mass transfer.

Lubrication filtration transfer in the first approximation obeys Darcy's law, [5]:

$$v=-\frac{k}{\mu}\nabla p \,, \quad (21)$$

where k is the the permeability coefficient of the porous surface structure;
μ is the dynamic viscosity coefficient of the lubricating film;
v is the average mass transfer rate of wear products.

From (20) and (21) after the corresponding transformations we obtain the mass transfer equation with a lubricating film:

$$\varepsilon\frac{\partial \rho}{\partial \tau}=De\Delta\rho+\frac{k}{\mu}\nabla(\rho\nabla\rho)-\frac{k}{\mu}g\nabla\rho^2+\nu \,, \quad (22)$$

where ε is the porosity or relative fraction of voids of the lubricant:

$$\varepsilon = \lim_{V \to 0} \frac{V - V_s}{V}, \tag{23}$$

where V is the the volume of the element of the porous structure;

V_s is the the total volume of the rigid frame of the same element;

ν is the density of surface bodies, $\nu = \rho g$;

g is the acceleration of gravity.

The transfer potential in the process of mass transfer is the chemical potential μ_i transferable component. The chemical potential is related to the concentration of the component ρ_i , with:

$$\nabla \mu_i = \left(\frac{\partial \mu_i}{\partial \rho_i} \right)_{p,T}, \nabla \rho_i + \left(\frac{\partial \mu_i}{\partial T} \right)_{\rho_i,T} \nabla T + \left(\frac{\partial \mu_i}{\partial \rho} \right)_{\rho_i,p} \nabla p . \tag{24}$$

For mass transfer at constant pressure, contact stresses and in isothermal conditions:

$$\nabla \mu_i = \left(\frac{\partial \mu_i}{\partial \rho_i} \right)_{p,T} \nabla \rho_i , \tag{25}$$

If the deviations of our system from the state of thermodynamic equilibrium are not so large, then the mass transfer flow can be described by a linear gradient law:

$$q_{mi} = -K \nabla \mu_i = -K \left(\frac{\partial \mu_i}{\partial \rho_i} \right)_{p,T} \nabla \rho_i = -D_i \nabla \rho_i . \tag{26}$$

Ziegler, [11], showed that the principle of thermodynamics of irreversible processes in combination with the principle of the smallest irreversible forces gives the maximum speed of dissipation. The speed of dissipation (dissipative function of the system) is determined by the ratio:

$$D(q_m) = \frac{dW}{d\tau} = g(q_m) q_m , \tag{26*}$$

where $g(q_m)$ is the generalized thermodynamic force that is proportional to the gradient of chemical potential.

Dissipative function can be introduced without the aid of irreversible force:

$$D(q_m) = T \left(\frac{dS}{d\tau} \right)_{ir} \geq 0 , \tag{27}$$

де $\left(\frac{dS}{d\tau} \right)_{ir}$ is the entropy flow due to the irreversible process of mass transfer.

The principle of maximum speed of dissipation requires ensuring the maximum $Д(q_m) = g(q_m) q_m$ due to the appropriate choice of transfer flow in the presence of restrictions on the species $F(q_m) = 0$. We get the solution from the relation:

$$\frac{\partial}{\partial q_m} \left[g(q_m) q_m - \lambda F(q_m) \right] = 0 . \tag{28}$$

Condition $F(q_m) = 0$, де $F(q_m) = Д(q_m) - g(q_m) q_m$ is a condition for the stability of the process of transition of the system to a state of thermodynamic equilibrium. From relation (28) it follows that:

$$g\left(q_m\right)=\frac{\lambda}{1+\lambda}\frac{\partial D}{\partial q_m}. \quad (29)$$

Determining the Lagrange multiplier λ, can be obtained:

$$g\left(q_m\right)=\left(\frac{\partial D}{\partial q_m}\right)^{-1} D\frac{\partial D}{\partial q_m}. \quad (30)$$

Dissipative functions of homogeneous processes satisfy the functional equation:

$$\frac{\partial D}{\partial q_m}q_m = f\left(D\right). \quad (31)$$

The condition of stability has the form:

$$f\left(D\right) > D \text{ при } D > 0. \quad (32)$$

Possible dissipative functions for the mass transfer process must be solutions of equation (31) with condition (32).

A special case (31) is equation:

$$\frac{\partial D}{\partial q_m}q_m = \alpha D. \quad (33)$$

The stability condition (32) in this case will be:

$$\alpha > 1. \quad (34)$$

Equation (30) can be converted by (31) into a more convenient relationship:

$$g\left(q_m\right)=\frac{D}{f\left(D\right)}\cdot\frac{\partial D}{\partial q_m}. \quad (35)$$

The solution of functional equation (33) will be the dissipative function of the form:

$$D = \text{const}\cdot q_m^{\alpha}, \quad \alpha > 1. \quad (36)$$

Using equations (35) and (36) we can obtain the following relationships between the gradient of chemical potential and mass transfer flow:

$$g = \text{const}\cdot q_m^{\alpha-1}, \ \alpha > 1. \quad (37)$$

Non-Markov process confirms that the magnitude of the mass transfer flow is determined by the entire "history" of mass transfer:

$$q_m = -\int_0^{\Delta T} M\left(\theta\right) g^n\left(\tau-\theta\right) d\theta, \ \ n \le 1. \quad (38)$$

If we explicitly determine the dependence of the magnitude of the transfer flux on the instantaneous value of the gradient of the chemical potential, the relationship (38) will take the form:

$$q_m = -M\left(\theta\right) g^n - \int_0^{\Delta T} M' g^n\left(\tau-\theta\right) d\theta, \ \ n \le 1. \quad (39)$$

Assumptions about the exponential attenuation of the relaxation function, ie:

$$M(\theta)=\frac{m}{\tau_m}\exp\left(-\frac{\theta}{\tau_m}\right), \tag{40}$$

converts (39) into a ratio of the form:

$$q_m=-[M(\theta)+m]g^n-\tau_m\frac{\partial q_m}{\partial\tau}. \tag{41}$$

In formulas (38) - (41) g is thegradient of the chemical potencial.

Therefore, formulas (22) - (41) represent a mathematical model of the actual mass transfer of the lubricating film in the formation of its limit state. From formulas (22) - (41) follows the value T_{ch} and T_{cr2}, [8, 9].

Conclusion

The nonlinear models of heat- and mass transfer for determination transition of temperatures by forming boundary lubricant film according to the conception of structure-thermodynamic approach of description the process of boundary lubricating is developed.

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Диха О.В., Старий А.Л. Моделі тепломасообміну при граничному змащуванні для визначення перехідних температур

В даний час все більше розвиваються кінетичні та термодинамічні методи оцінки змащувальної дії масел. При граничному терті зменшення тертя і зносу поверхонь відбувається за рахунок здатності мастила утворювати на поверхні шари адсорбційного або хімічного походження. Для математичного опису процесів у підсистемах та переходу між ними необхідно використовувати аналітичні моделі переходів температури та зносу в режимі граничного змащування. За базову розрахункову залежність прийнято рівняння Фур'є теплопровідності. Передбачається, що процес поширення тепла за умов утворення мастильних плівок не є марковським, тобто величина теплового потоку визначається всією «історією» теплообміну в певному елементарному об'ємі. Рівняння руху мастильної плівки по поверхні тіла, що змащується, виходить з рівняння руху для ньютонівського безперервного середовища. В результаті отримано нелінійні моделі тепломасообміну для визначення температур переходу при формуванні граничних мастильних плівок у концепції структурно-термодинамічних підходів до опису процесів граничного змащування поверхонь.

Ключьові слова: граничне мащення, перехідні температури, математична модель

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Basic approaches and requirements for the design of tribological polymer composite materials with high-modulus fillers

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Abstract

Based on a combination of a system-oriented approach and a synergetic concept, the requirements for the design of tribological polymer composite materials with high-modulus fillers are formed. These materials are considered as an open dynamic system that evolves during operation. The principles of the synergetic concept for tribotechnical systems taking into account the theory of evolution and self-organization to ensure its self-governing and self-supporting development are considered. It is revealed that in the process of interaction of elements of the tribosystem the cooperation of local areas of their materials is formed with the emergence of a critical number of such areas and the creation of an information field about their functioning. The direction of self-organization of processes and states of parts materials in the tribotechnical system and expediency of using the conclusions of the synergetic concept in the construction of polymer composite materials, as well as their nonequilibrium are shown. The issues of creation of tribophysical bases of wear resistance of tribotechnical systems with conjugations of the details made or strengthened by polymeric composite materials are considered. Polymer composite materials are considered as a set of interacting ensembles of local areas, the principle of maximum wear resistance (reliability) is used. Tribological principles and requirements to creation and substantiation of expediency and efficiency of use of high-modulus fillers in polymers are formulated.

Key words: polymer composite material, high-modulus filler, tribotechnical system, system-oriented approach, synergetic concept

Introduction

The use of parts made of polymer composites and restored by coating these materials has shown their effectiveness in increasing the durability of systems and units of machines. However, there is a problem of optimizing the composition of polymer composites, the content of fillers, their distribution in the polymer matrix. Poorly developed issues of modification of the matrix and fillers of polymeric composite materials (PCM) by flows of matter and physical fields [1, 2].

In [2-5] it was shown that under some conditions of friction the structure of the heterogeneous PCM material, which corresponds to the Sharpy principles, is not optimal. Heterogeneous materials of PCM applied on the surface of machine parts must have high wear resistance, thermal stability of phases, the ability to adjust the morphology of the structure and the direction of its elements. Their efficiency has been insufficiently studied due to significant differences in views on the impact of structural features of PCM and the lack of data on the combination of components in a set of characteristics and their properties. There are no generalized criteria for selecting optimal wear resistance compositions. It is possible to increase the wear resistance of PCM by improving their structure, the optimal combination of characteristics and properties of components, the implementation of processes and the state of self-organization.

Literature review

Along with extensive studies of the processes of friction and wear of materials with homogeneous and microheterogeneous structure [5], the mechanism of wear of PCM with micro- and macroheterogeneous structure with high-modulus filler is insufficient [6]. In the works of V.Ya. Belousova [3], I.M. Borodina [7], V.I. Savulyak [8], V.V. Aulina, [9], I.M. Fedorchenko [10], N.P. Suh [11-13], M.F. Ashby [14] and others, it is noted that from a number of known types of composite materials PKM is the most promising. In terms of the formation of new, wear-resistant PKM and coatings, it is advisable to proceed from the estimated estimates of optimization of the structure, content size and distribution of high-modulus fillers, the characteristics of their materials. The complexity and versatility of PCM wear processes, according to VP Bondarenko, VV Aulina, VI Savulyak and other authors, forces to introduce empirical constants and phenomenological functions that have no real analogues, or to create simplified models of friction surfaces and schemes of wear mechanism [4, 15, 16].

The connection between the wear process of PCM and their mechanical properties is given in [6, 17]. The results of PCM wear resistance studies with homogeneous and heterogeneous structure show that in the first case it is lower than in the second due to faster equalization of contact pressure. The phenomenon of spontaneous installation and maintenance of stationary wear and tear mode of PCM is also due to the existence of feedback. Based on the ideal conditions of sliding contact, in [6] with the help of friction surface models, the tribotechnical characteristics of PCM with different structure and different composition were calculated.

The approach to solving the problem of managing the properties of PCM is of considerable interest and requires innovative developments in the direction of analytical research on ways to improve wear resistance and optimal selection of conjugate surfaces of parts. Since there is no mathematical or physical model that takes into account all the features of the process of friction and wear of PCM today, it is necessary to conduct an analytical study of the dependence of wear resistance on the structure and complex properties of components and PCM in general. Varying the content of the components of PCM, with their unchanging nature, change the total contact pressure of the composition and its structure [18-21], providing the required level of properties that affect wear resistance.

It is revealed that in the conditions of friction and wear elastic and plastic deformations are the main processes that initiate the emergence and development of physical, chemical and mechanical processes in the surface layers of PCM [4, 15]. It is shown that in PCM the main share of loading is received by a filler. Reinforcing fillers prevent the movement of dislocations in the matrix, which is subject to plastic deformation, limiting it [15]. At the same time it is strengthened by increasing the content of filler and reducing the distance between its particles. In [3, 8] it was found that depending on the structural state of the PCM, the magnitude of the accumulated plastic deformation is not the same, which causes different processes of relaxation processes. The type and dispersion of filler particles (carbides, borides, oxides, intermetallics) in the polymer matrix, which are barriers to plastic deformation, significantly affect the inhibition of the relaxation process, but it is not known how the degree of dispersion of the filler affects the properties of PCM, filler – for stress relaxation and wear process.

E.A. Adirovich and D.I. Blokhintsev [22] proposed a dynamic approach to the study of friction and wear of materials, which was further developed in the works of S.V. Krysova [23] and other scientists [24, 25]. The material in the friction zone is considered as a system of excited oscillators that are attenuated in accordance with the relaxation properties, and the assumption is made about the possibility of energy dissipation by wave fluxes [24, 23]. This is one of the manifestations of structural self-organization of PCM and a method of increasing their wear resistance.

L.J. Bershadsky [26-28] proposed information-dynamic and structural-dynamic concepts, in which friction is considered as a stochastic system of linear oscillators (elementary excitations), as synergistic effects (autosynchronization, autowave parameters, etc.) due to the flow correlation of these excitations. These concepts continue to evolve.

In the thermodynamic approach to friction [29, 30], quasi-static and kinetic friction are considered and generalized principles of designing the material of parts with a given wear resistance are proposed: the principle of rheodynamic localization; the principle of dissipative heterogeneity; the principle of triboshielding.

In the synergetic approach [31-34] it is important to use the synergetic concept in friction and wear, which determines the conditions of processes and formation of states of self-organization of surface layers during running, operation and technological processing of parts, especially in strengthening, restoration and modification. In this case, the triad coupling of parts must have minimal wear, and therefore maximum wear resistance, which deserves special attention.

Analysis of approaches to the study of the ability of materials of PCM components to resist wear [35-38] indicates the need to combine the physical nature of the set of processes and states with their tribological interpretation. In this regard, it is advisable to interpret and solve the problem of increasing the wear resistance of PCM from a tribophysical point of view, including: a set of characteristics and properties of their surface layers, interaction with the working (technological) environment, development of rational and optimal methods of process and state management PCM during hardening and modification and operation [39]. This problem is extremely relevant in tribology and tribology. To solve it, a combination of a system-oriented approach and a synergetic concept in the study of processes, states and functioning of PCM in different operating conditions and their computer modeling is proposed.

Purpose

The aim of this work is to elucidate the possibilities of a system-oriented approach and synergetic concept of designing tribological polymer composite materials with high-modulus fillers and developing a system of requirements for them.

Results

The system-oriented approach involves consideration of conjugations of parts operating in working (technological) environments of tribotechnical system, consisting of interacting parts of components, systems and units of machines, working (technological) environment, structure, characteristics and properties of PCM materials and wear and tear change over time. Since the process of development of any tribotechnical system of machines must be considered from a systemic point of view, only a system-oriented approach makes it possible to understand the nature of irreversible changes that occur in the PCM. The principle of symmetry [40-42], according to which the properties and relationships of system elements are determined, is formulated as a law in the composition of scientific theories as a methodological principle. In this sense, the principle of symmetry can be understood as a generalization of the principles of relativity and invariance [43]. The dialectical relationship of simple and complex in the tribotechnical system with PCM is manifested in the fact that the structure of the materials of the matrix and filler changes during operation. In this case, such a system should be considered from a dynamic point of view, ie with the emergence of complexity [40-44].

The basis of the synergetic concept of research conditions and mechanisms for implementing processes and states of different types of self-organization PMK and working (technological) environment in the tribotechnical system is a set of interrelated principles, which is that changing the structure, characteristics and properties of component materials occurs due to the collective interaction of their components and physical fields.

The principles of the synergetic concept are mainly methodological principles, to which the following requirements apply: the relation of ring causality is observed; their number is limited; mappings of space of processes and states and the theory of dynamic systems are used [45-47]. In identifying the relationship between these principles, it is advisable to use their development in mathematical, logical and philosophical aspects [48], and any evolutionary process in the tribotechnical system can be represented as changes in conditional states of order and chaos, combined processes and phase transitions (PhT) in materials of details and working (technological) environments.

In essence, the synergetic concept contains the principles of subordination and compliance, selection and Kozma Prutkov, which are relevant to the means of observation. At the same time, observability emphasizes the limitations and relativity of ideas about the studied tribotechnical system and means the relativity of interpretations to its scale, initial and expected results and makes the system open to methodological and systematic interpretations, combining synergetic concept with system-oriented approach. On the other hand, the problem of interpreting the tribotechnical system is similar to the problem of identification and is characterized by the fact that collective interactions do not change its total energy, but redistribute between elements: conjugate parts and working (technological) environment.

The theory of evolution and self-organization teaches the art of soft control systems: weak influences that are resonant, extremely effective and must meet the internal trends of tribotechnical systems. The main problem is how to push the tribotechnical system on one of the own and favorable ways with small resonant action, providing self-managing and self-supporting development. This applies, first of all, to the structures of PCM parts and working (technological) environment, which are implemented in a complex tribotechnical system through the influence of resonant. Their evolution itself is contradictory, as it consists of both orderly and unregulated processes, but is subject to the law of harmony, the content of which reflects the concept of "golden section" [40, 44, 49]. If the regularities of changes in the structure of PCM in tribotechnical systems allow several equally probable states, then the one that corresponds to the minimum entropy is realized. Other features of the evolution of systems are associated with the emergence of a new type of structure. This is preceded by an increase in fluctuations at the macro level, the development of entropy exports to the environment and the transition from the old dissipative structures to new secondary structures in the materials [50].

In the process of interaction of the elements of the tribotechnical system reveal the cooperation (collective action, coherence) of their local areas, the emergence of a critical number of such areas and the creation of a single information field about their functioning. The complex of selectively involved local regions takes the form of mutual assistance in obtaining a useful result in the tribotechnical system [51]. In this case, the principle and theory of evolutionism [52-54] of systems does not contradict the two great theories of evolution of L. Boltzmann and Charles Darwin. The idea of selection plays an important role in it: the new arises as a result of the selection of the most effective forms, and inefficient innovations are rejected by the development process. This emphasizes the most important pattern of systems: the focus of their development to improve structural organization, ie, self-organization, self-development [53-56]. Today, the idea of evolutionism is a regulatory principle that focuses on identifying specific patterns of evolution of tribotechnical systems at all its structural levels (macro-, meso-, micro-, nano-) and stages of self-organization. In this regard, the principle of "Razor Okkami" is a measure of thrift or the law of economy [44].

The central place in the main synergetic principle is given to the principle of self-organization, which is that the internal activity of the tribotechnical system is opposed to the disorganizing element of entropy and, under certain conditions, leads to self-motion. This determines the following methodological direction of self-organization of processes and states in the tribotechnical system:

– processes and states must be irreversible;

– the system is open and remote from the state of thermodynamic equilibrium;

– entropy produced in the system does not accumulate in it, but is excreted, from the external environment there is a flow of negentropy;

– in nonequilibrium systems fluctuations accumulate and amplify and obey the principle of positive feedback;

– the process of different types of self-organization begins at the micro and nanoscale with local areas of system elements and the intensification of fluctuations under the influence of external influences;

– as a result of increasing fluctuations, the system becomes more unstable, the previous order and structure are destroyed and qualitatively new ones appear when energy is dissipated into the external environment;

– the emergence of a new order occurs spontaneously at the time of extreme instability, when the materials of the elements of the system acquire significant coherence;

– the development of the system is a nonlinear process, and therefore can be described by a nonlinear differential equation;

– characteristics and properties of materials of elements of the system have a probabilistic nature and randomness has a significant impact on their further development;

– any qualitative transition and the emergence of a new order in the system are associated with the bifurcation point (choice of path of development);

– an adequate description of the development of the tribotechnical system involves taking into account its prehistory, etc.

This indicates that the processes and states of self-organization, as a positive result of evolution, occur due to intrinsic tribotechnical systems, which are based on two mutually exclusive trends: the establishment of a certain order and the emergence of self-organization and the formation of a new structure; in the course of further development the previous order is destroyed, and the relationships between the local regions of the materials of the elements are subject to change with the spontaneous establishment of a new order and the emergence of new dissipative and secondary structures.

The analysis of processes of development of tribotechnical systems during running-in and operation testifies to expediency of use thus conclusions of the synergetic concept:

– self-organization reveals the process of development of various forms of systems;

– any development process can be carried out in open systems;

– the existence of self-organization confirms the principle of self-movement and internal activity of the materials of the elements;

– the openness of the system is an insufficient condition for its self-organization, as there is a need for a state remote from thermodynamic equilibrium;

– at each stage of development of the system self-organization acquires specific features: the higher the evolutionary system, the greater the requirements for the conditions of implementation of self-organization and more complex processes and states;

– the source and initial moment of development of the system associated with the emergence of a new, is the emergence of a set of coincidences;

– fluctuations or random deviations direct the development of nonequilibrium systems with the gradual accumulation and intensification of fluctuations;

– irreversibility, instability and nonequilibrium – the most fundamental properties of systems than stability and equilibrium, etc.

According to the theory of nonequilibrium processes [51, 57-59], the properties of tribotechnical systems remote from the equilibrium state become unstable and their return to the initial state is optional. However, their behavior is ambiguous, but there are effects of coordination, correcting the behavior of elements at macroscopic distances and time intervals [60]. Cooperatively coordinated behavior determines the processes of ordering, the emergence of certain structures out of chaos, their transformation and complication [60]. The greater the deviation from equilibrium, the greater the coverage of correlations and relationships, the higher the consistency of processes characterized by nonlinearity and the presence of positive and negative feedback [63, 64], and the possibility of control over the tribotechnical system.

In the process of evolution, the external contribution to the total entropy of a tribotechnical system can be arbitrary, depending on the parameters of the external environment and the nature of its interaction with the system. There are two types of situations [65]:

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

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

– total entropy is constant and maximum for these conditions of operation of the tribotechnical system, but less than the entropy of equilibrium:

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

When the entropy flux is equal to its production ($\Phi_S = \sigma_S$), the tribotechnical system is in a stable steady state or a state of current equilibrium. If the internal entropy $d_iS > 0$, then the energy processes in the system are always dissipative, ie accompanied by a decrease and scattering of energy. Energy dissipation is the main sign of current equilibrium, but, in accordance with the principle of self-permeability of equilibrium, the system can not get out of it spontaneously and under external influence intensified processes to compensate, like the manifestation of electromagnetic induction [24, 25]. According to the principle of minimum entropy production, the laws of nature [66] suggest several options for the development process (organization), and the one that meets the minimum energy dissipation is realized. In this case, the driving force of the processes of self-organization of materials of the elements of the tribotechnical system is the PhT or their sequence, resulting in a transition to a more ordered state, corresponding to the lower symmetry.

Among the extreme principles of the synergetic concept and one of the key provisions of modern physics, including and tribophysics is the principle of stationary or least action (PLA) [40]: among all possible movements (directions of development) of elements and systems in general is realized that for which the minimum is the product of energy consumed at the time of action. The principle makes it possible to obtain the equation of motion of the system using the stationary value of a special functional - action [40, 67].

The combination of system-oriented approach and synergetic concept, as an integrative search for patterns in tribology PCM, allows to take into account the results of research on improving wear resistance, as well as a set of properties and characteristics of materials triboelements, working (technological) environments, friction and wear in tribotechnical system.

Creation of tribophysical bases of wear resistance of tribotechnical systems, with conjugated details, made or strengthened by PCM, using the system-oriented approach and synergetic concept, has independent, methodological and scientific value as allows to specify subject idea of wear resistance and to expand information on processes in materials. working (technological) environment, on the limits of their interaction and the evolution of states. In essence, the tribophysical direction in mechanical engineering confirms the implementation of a new mechanism of friction based on the effect of self-organization. Unlike known methods, concepts and approaches, this methodology makes it possible to establish the relationship of various process parameters, state and material properties of parts from a tribophysical point of view.

The kinetics of the exchange process of interaction of ensembles of local regions of PCM is described by the stochastic differential equation:

$$dx_j^i/dt = f_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right) - g_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right), \tag{3}$$

where $f_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right)$, $g_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right)$ is the functions of the rate of accumulation and scattering of internal energy. For a simplified consideration of the functioning of the local regions of the PCM, we believe that the transition of the state of the ensemble ε_i to ε_e causes an almost instantaneous change in the state of the triboelement material. Analysis of the structural organization of the PCM was performed using integer functions:

$$N(t) = \left[N_1(t), N_2(t), ...N_i(t), ..., N_n(t)\right], \tag{4}$$

where $N_i(t)$ is the number of identical ensembles ε_i at each moment of time t. The structural entropy and the probabilistic state are equal to:

$$S_c(P_\alpha) = -\sum_{i=1}^{n} P_{ci} \cdot \ln P_{ci}; \qquad P_{ci}(t) = N_i(t) \Big/ \sum_{i=1}^{n} N_i(t). \tag{5}$$

In such conditions of operation of PCM it is possible to use the principle of the maximum wear resistance (reliability) [68, 69] according to which conjugation of details, working in the working (technological) environment, tries to minimize the interaction with it. The measure of such interaction is the deviation of the parameters of tribotechnical systems from the optimal values, which is consistent with the principle of structural adaptability, formulated by B.I. Kostecki, L.I. Bershadsky, V.G. Kanarchuk, M.A. Boucher in the works [70-72]. The principle of maximum wear resistance (reliability) is special in the dynamics of structural adaptability of triboelement materials (conjugations of parts, parts and working (technological) environment), and dynamic equilibrium in tribotechnical systems as a whole obeys the principle of least action [40]. The equation of the entropy balance of the local region of the PCM has the form:

$$\overline{\rho}_{\partial i}(dS_i/dT_i)+divS_i=\xi(S_i)\,, \quad (6)$$

where dS_i/dT_i, $divS_i$, $\xi(S_i)$, $\overline{\rho}_{\partial i}$ are the inflow, outflow, entropy growth and average density of defects in the *i*-th local region.

Since the rate of destruction in local areas of PKM is controlled by the rate of entropy production, to maintain the state of quasi-wear of the surface layers of parts it is necessary to maintain its saturation with vacancies, ensure high density of mobile and reduce the density of stationary dislocations. Based on modern ideas of the theory of friction and wear in the works of V.A. Bieloho, V.Ia. Bielousova, D.M. Harkunova, B.I. Kostetskoho, I.V. Krahelskoho, A.P. Semenova, I.M. Fedorchenka, V.P. Bondarenka, V.V. Aulina, V.I. Savuliaka, etc., it is possible to formulate a number of tribological principles of creation and substantiation of expediency and efficiency of use of PCM with high-modular fillers:

– the structure of PCM should be heterogeneous and consist of solid fillers (inclusions), evenly distributed in the polymeric elastic-plastic matrix;

– the structure of the PCM should not change significantly during friction, but can be rebuilt into a more favorable structure without weakening;

– the layer of PKM applied to the surface of the part must have less strength than the layers below (positive gradient rule);

– under the influence of working (technological) or external environments in PCM there should be no significant structural changes, deterioration of characteristics of durability and plasticity;

– it is recommended to include high-modulus substances and substances capable of working as a solid lubricant in the PCM;

– there must be an adhesive bond between the structural components of the PCM;

– anti-emergency additives introduced into the friction zone should not significantly reduce the strength of PCM;

– coefficients of friction of solid fillers (inclusions) among themselves and on the material of the PCM matrix should be minimal, etc.

Note that the requirements for the structure and properties of wear-resistant PCM can be clarified and specified in the process of experimental and theoretical studies depending on the type of mating parts, friction conditions and type of wear: minimizing porosity; providing a heterogeneous structure of the material with a uniform distribution of the filler in the elastic-plastic matrix; the adhesive bond between the components must be strong enough. Ideal, in terms of tribotechnical requirements, is the three-phase structure of PCM: elastic-plastic matrix, solid wear-resistant high-modulus fillers (inclusions) and solid lubricant particles to ensure the implementation of the rule of positive gradient of properties.

The analysis of operational characteristics of PCM of tribotechnical appointment shows that they are defined by conditions of work of tribocoupling of details and in wide limits vary: low values of coefficient of friction and high wear resistance; combination of optimum volume and surface strength with easy hardness of surfaces of conjugated details and sufficient viscosity to exclude brittle fracture; high fatigue strength; ability to form layers of secondary structures; sufficient thermal conductivity and optimal values of the coefficient of thermal expansion (CTE); availability of solid or liquid lubricants; economy and manufacturability in the manufacture.

The change in the mechanical properties of the materials of the surface layers of PCM parts is due to the reduction of free surface energy and, as a consequence, the reduction of work required to increase the surface, revealed mechanisms for converting mechanical energy into other forms of energy.

This makes it possible to make some generalizations that can be used to increase the wear resistance of parts made of PCM:

– mechanical methods of activation radically affect the reactivity of the surface layers of the materials of parts;

– mechanical activation is a method of directed regulation of physical, physicochemical and tribological properties of working surfaces and surface layers of parts;

– under the influence of mechanical activation there are qualitative and quantitative changes in the nature of chemical bonds and the transformation of chemical compositions of the surface layers of parts;

– mechanochemical methods of activation stimulate the development of heterogeneous reactions in the near-surface layers.

Conclusions

1. The methodology of combining a system-oriented approach and a synergetic concept in the design of polymer composite materials for the manufacture of couplings of parts, systems and units of machines and coatings is formulated.

2. In the system-oriented approach, polymer composite materials are considered as systems with components: matrix, high-modulus fillers, additives of particles of solid ink materials.

3. It is found out that the basic synergetic concept of research of conditions and mechanisms of realization of processes and states of various types of self-organization of polymeric composite materials and working (technological) environment in tribotechnical system.

4. The set of principles contained in the synergetic concept is considered: subordination and conformity, choice, etc. The expediency of using the conclusions of the synergetic concept in the construction of polymer composite materials is clarified.

5. The use of the theory of evolution and self-organization of materials of the tribotechnical system, conditions of providing self-managing and self-supporting its development are considered.

6. Based on the principle of self-organization of elements in the tribotechnical system, the methodological orientation of self-organization of different types, processes and states of polymeric composite materials with high-modulus filler is revealed.

7. Since nonequilibrium processes are observed in the friction and wear of conjugated parts in the tribotechnical system, the theory of nonequilibrium processes should be taken into account when designing polymer composite materials, taking into account the evolution of materials and the effects of matching and correcting their behavior.

8. From the theoretical point of view, the nature of entropy change in the tribotechnical system, energy dissipation, the extreme principle of synergetic concept and the principle of stationary or nonlinear action are considered.

9. Polymer composite material is considered as a set of interacting ensembles of local areas. The analysis of their structural organization is performed using an integer function taking into account the structural entropy and probabilistic state. In the conditions of operation of polymer composite material it is possible to use the principle of maximum wear resistance (reliability), according to which the conjugation of parts, assemblies, units of machines operating in the working (technological) environment minimizes its interaction with it.

10. A number of tribological principles of creation and substantiation of expediency and efficiency of use of polymeric composite materials and requirements to their structure and properties are formulated. Generalizations are made which can be used at increase of wear resistance of the details made of polymeric composite materials.

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Аулін В.В., Гриньків А.В., Смаль В.В., Лисенко С.В., Пашинський М.В., Катеринич С.Е, Лівіцький О.М. Основні підходи та вимоги до конструювання трибологічних полімерних композитних матеріалів з високомодульними наповнювачами

В роботі на основі поєднання системно-спрямованого підходу і синергетичної концепції сформовані вимоги до конструювання трибологічних полімерних композитних матеріалів з високомодульними наповнювачами. Ці матеріали розглядаються як відкрита динамічна система, яка еволюційно розвивається в процесі експлуатації. Розглянуті принципи синергетичної концепції для триботехнічних систем з урахуванням теорії еволюції і самоорганізації для забезпечення її самокеруючого і самопідтримуючого розвитку. Виявлено, що в процесі взаємодії елементів трибосистеми формується кооперативність локальних областей їх матеріалів з виникненням критичного числа таких областей й створення інформаційного поля про їх функціонування. Показано спрямованість самоорганізації процесів і станів матеріалів деталей в триботехнічній системі та доцільність використання висновків синергетичної концепції при конструюванні полімерних композитних матеріалів, а також їх нерівноважність. Розглянуті питання створення трибофізичних основ зносостійкості триботехнічних систем зі спряженнями деталей, виготовлених або зміцнених полімерними композитними матеріалами. Полімерні композитні матеріали розглянуті як сукупність взаємодіючих ансамблів локальних областей використано принцип максимальної зносостійкості (надійності). Сформульовані трибологічні принципи та вимоги до створення і обґрунтування доцільності і ефективності використання високомодульних наповнювачів в полімерах.

Ключові слова: полімерний композитний матеріал, високомодульний наповнювач, триботехнічна система, системно-спрямований підхід, синергетична концепція

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Use of structural anomalies in steel gas-thermal coatings during increased wear-out

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Abstract

The structure of gas-thermal coatings made of wire materials has been studied by determining the most efficient methods of controlling the process of structure formation to achieve the highest physical and mechanical properties of renewable surfaces of vehicle parts.

The effect of formation of anomaly amount of residual austenite in sprayed steel coatings was established. Technologies of application of the “austenitic effect” is suggested here to increase a coating wear-resistance. It is determined that the main factors influencing the content of residual austenite in hardened steel are the cooling rate of steel, the concentration of alloying elements in the austenitic phase, as well as thermal stabilization of austenite during self-tempering.

It is shown that to ensure the formation in the structure of sprayed coatings of alloy structural, tool and corrosion-resistant steels of metastable austenite, which has a low flow temperature of deformation gamma-alpha transformation, which corresponds to the operating temperatures of sliding friction units, it is necessary to achieve certain coating conditions. wire spraying, cooling rate of molten particles and the degree of their oxidation). One of the most probable reasons for the appearance of the "austenitic effect" in coatings is the heating of the surface layer to a temperature that promotes thermal stabilization of austenite, as well as saturation of melt droplets with alloying elements (primarily chromium) and impurities (carbon, nitrogen) in flames. The relatively low flight speed of molten steel particles and the high concentration of propane containing carbon in the combustion products contribute to the deep saturation of the melt droplets with carbon. It is likely that these circumstances are associated with a high content of residual austenite in the coatings obtained by gas-flame spraying. An additional factor that increases the resistance of austenite in the sprayed coating may be the saturation of the droplets of the melt with carbon during melting and spraying using a propane flame.

The studies under discussion have suggested that both for the method of gas-flame spraying and for the method of electric arc spraying, there are modes and steels for spraying that allow the formation of large amounts of metastable austenite in coatings, which in the process of tribocoupling will turn into martensite.On the basis of the carried-out researches technologies of restoration of details of vehicles by drawing multipurpose coverings in which the choice of a method of heating of a wire at spraying is carried out depending on temperature of the beginning of martensitic transformation of a wire material are offered.

Key words: electric arc spraying, gas flame spraying, wear resistance, residual austenite, resurfacing, gas thermal coating

State of the matter

The mehods of multifunctional coatings application based on the wire-shaped materail spraying have proved to be the most efficient methods of surface reconditioning, strengthening and protection of wearing surfaces of transportation means (TM) parts of components and assemblies. At the parts of transportation means reconditioning it’s preferable to use gas flame spraying (GFS) and electric arc spraying (EAS) of the wire-shaped materail [2] to save time of the spraying process due to the increase of the sprayed particles flying speed by means of gas heating by an uninterrapted power supply [3].

Purpose of the study

The purpose of the study was to investigate the structure of gas thermal coatings made of wire-shaped materials by means of finding the most efficient methods of structure formation process control to achieve the most beneficial physical-mechanical properties of reconditioned surfaces of the transportation means parts.

Research procedure

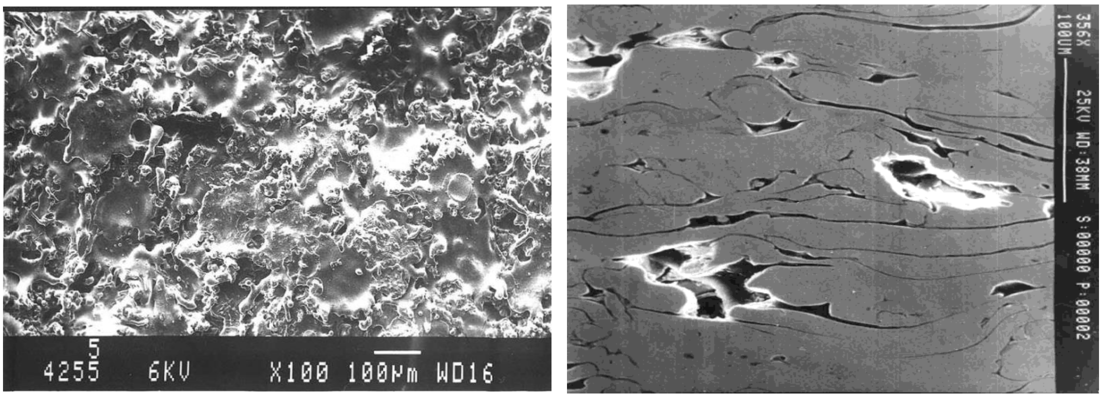
Some structural specific features of gas thermal coatings (GTC) obtained by steel wire spraying of martensite (40Kh13) and austenite class (Kh18N10T) by different methods of gas flame spraying (GFS) and electric arc spraying (EAS) have been studied [3] in the following modes:

- mode 1 – spraying of the material melted in a flame body of propan-oxygen flame by a high-speed air stream;
- mode 2 - spraying of the material melted in an electric arc by a jet stream of propan-air mixture flame products rich in propan (deoxidizing atmosphere);
- mode 3 - spraying of the material melted in an electric arc by a jet stream of propan-air mixture flame products rich in air (oxidizing atmosphere);
- mode 4 – spraying of the material melted in an electric arc by high-speed air stream.

To increase the coating adhesion with the reconditioned surface made of steel 45 we have used an intermediate layer made of alloy Kh20N80. The flying speed of the sprayed particles was ranging within 100 ... 130 m/c (modes 1, 4) 400 ... 500 m/c (modes 2, 3). The size of particles forming the coating was ranging within 5 ... 40 mkm.

Results of their study and their discussion

The coatings obtained due to the wire-shaped materials spraying are in their structure similar to gas thermal powder coatings. Nevertheless, in case of gas thermal spraying of powder materials some separate particles can not be enough melted or can be heated to premelting temperatures, but during the spraying of one-piece wires the coating layer is being formed only from the melted particles (otherwise the drops separation from the wire will not occur). It results in larger deformation of particles than in case of powder coatings and less sponginess (fig. 1).



a) b)

Fig. 1. Microtopography (a) and microstructure (b) of steel gas-thermal coating

The formation of coating is accompanying with the intense impact of flame body on the particles of spraying material and their interaction during the process of coating layer formation on the reconditioned surface of the part. In this case, due to the processes of high-speed crystalization, deformation and drawing innthe layer of formed coating, some oxides are occurring, a part of alloying elements is burning up. Thus, structural state and properties of obtained coatings on the reconditioned surfaces depend on the combination of influence of all parameters of the spray application.

Most of oxides are formed due to the contact of melted particles with air. That is why the impact of spraying air consumption on the amount of oxygen in the coatings, obtained in mode 1 by gas flame spraying and in mode 4 by electric arc spraying has been studied. The volume share of the oxides in gas thermal coatings had been studied earlier and the results were described in paper [3].

Under gas-thermal spraying of wires conditions the maximum oxygen content in the coatings was ranging within 1,50 ... 1,70% and it can be obtained at spraying air consumption over 0,35 m^3/min. (fig. 2).

Further increase of spraying air consumption has not resulted in the oxygen concdentration increase. Oxygen content in electric arc coatings is 2,5 ... 3 times higher than in gas flame ones. Moreover, the maximum concentration 3,8% is reached under spraying air consumption conditions of nearly 0,5 m^3/min.

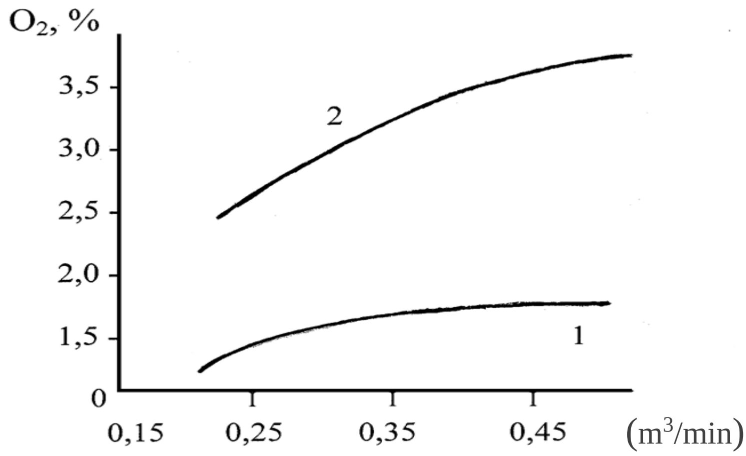


Fig. 2. The effect of the spraying air consumption on the amount of oxygen in the coatings obtained by gas-flame spraying in mode 1 (1) and electric arc spraying in mode 4 (2)

One of the most probable reasons of "austenite effect" taking place in the coatings is the upper layer heating up to the temperature 500-670 K which facilitates the thermal stabilization of austenite and the saturation of the melt drops with alloying elements (first of all with chromium) and impurities (carbon, nitrogen) during the wire melting in the flame. This is proved by the absence of carbides particles $Cr_{23}C_6$ in the coating. One more factor increasing the austenite resistance in the sprayedcoating can be the saturation of melt drops with carbon during the process of melting and spraying using propan flame (table 1).

Table 1

The effect of the composition of the combustible mixture, forming a torch in gas-flame and electric arc spraying on the content of carbon and oxygen in the coatings of steel 40Kh13

Spraying mode	Oxygen-propan volume ratio in the mixture	Oxygen content in the coating, %	Carbon content in the coating, %
GFS mode 1	Propan-oxygen mixture, ratio 1/4	1,3	0,6-0,7
EAS mode 2	Propan-air mixture, ratio1/18	1,4	0,5
mode 3	Propan-air mixture, ratio1/30	2,2	0,4
mode 4	Pure air	3,3-3,5	0,3-0,4

Relatively low flying speed of melted steel particles and high concentration of propan containing carbon in combustion products contribute to deep saturation of melt drops with carbon. It's quite possible that a deep content of residual austenite in the coatings obtained by gas flame spraying in connected with these circumstances.

A bit smaller amount of austenite in the coattings obtained by electric arc spraying in the deoxidizing atmosphere (in mode 2) of the spraying torch can be explained by considerably higher flying speed of melted particles which is a specific feature of this way of spraying. In this case the processes of diffusion saturation of melt drops with carbon from the deoxidizing atmosphere of propan-air mixture combustion products have no time to occur (the time of melted drops flight in the combustion products atmosphere is not more than $5 \cdot 10^{-4}$c) and the content of residual austenite in a coating layer is decreasing to
$\cong$ 20 об. %.

The increase of oxygen concentration in the mixture was not accompanied with the change of residual austenite content in the coating obtained under super sound speed of melted particles flying conditions (mode 3)

and under relatively low speed of melted particles flying conditions (mode 4). In both spraying options the residual austenite content in the coating does not exceed 20
vol. %. Perhaps, such content of residual austenite in steel 40KhN is balanced for the case of complete decomposition of chromium carbides in it and the implementation of typical of GFS cooling conditions of melted steel drops.

To activate the decay process of residual austenite in the gas-flame sprayed coating the tempering was conducted at temperature 520, 620, 720, 770 i 820 K. The holding time of the tempering was 9 min. The X-ray phase analysis data have proved that the decay of stabilized residual austenite of the coating sprayed layer was taking place due to the high pressure at temperature range within 770 ... 820 K. At lower temperature the tempering was not accompanied with the decrease of residual austenite amount in the coating layer. High temperature of the tempering necessary for the sprayed layer austenite decay is caused by the temperature of chromium carbides development in it and after their separation the residual austenite resistance has drastically decreased. The sprayed layer hardness after tempering at 770 K was equal to 2800 MPa.

The sprayed coatings in their initial state had the hardness of 360 ... 380 MPa, microhardness HV_{30} = 2650 MPa, residual austenite content 40 ... 45 vol.% (Fig. 3).

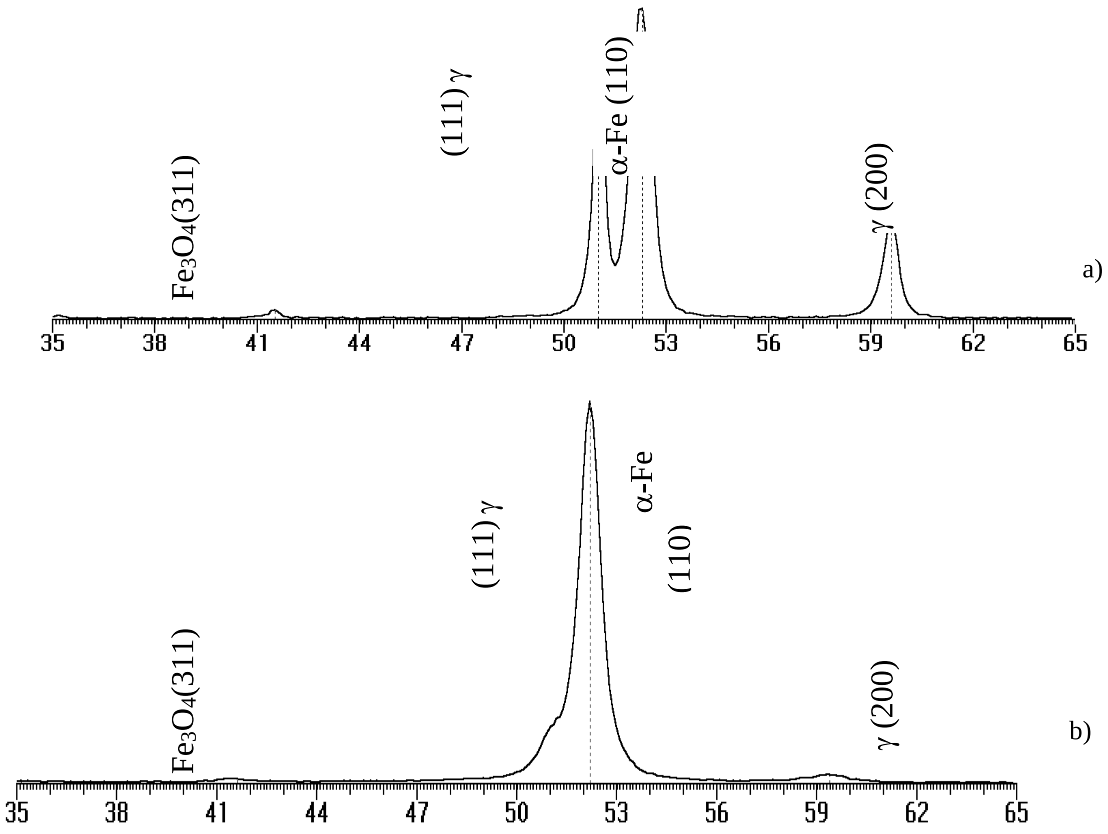


Fig. 3. Fragments of X-ray diffraction patterns from the surface layers of coatings after gas-flame (a) and electric arc spraying (b)

One of the main requirements to satisfy the upper layers of the reconditioned parts of tribocouples is plastic property during the initial period of friction to accelerate the process of underworking, and also high wear resistance, hardness, adhesion to lubrication during further operation of the assemby. This requirement dealing with steels can be met only in case when two-phase structure was formed inthe steels containing metastable austenite of hardness 200 - 300 HV. In the process of underworking as a result of intensive plastic deformation the metastable austenite is transformed into the wear resistant and hard martensite (HV = 700 ... 800) as the deformation $\gamma \rightarrow \alpha$ transformation was taking place.

The conducted investigation made possible to assume that for both the gas-flame spraying method and for electric arc spraying method there are such modes and steels for spraying which allow to provide the formation of large amount of metastable austenite in the coatings which will be transformed in martensite during the process of tribocoupling.

In cast steels to obtaine metastable austenite one should apply the special alloy method, complex thermal and thermomechanical treatment whose conducting is mostly economically inadvisable.

To provide the metastable austenite formation with low temperature of deformation $\gamma \rightarrow \alpha$ transformation (temperature $M_{Д}$) corresponding to the operating temperature of sliding friction units (270-20 K) in the sprayed coating structure, one should reach the determined conditions of the coating formation, namely wire heating temperature (overheating above the point of melting), the temperature of its spraying, speed of melted particles cooling and the degree of their oxydation resulted in the change of alloying constituents concentration.

The experimental study has proved the relation between the temperature value of the beginning of martensite transformation of wire material T_M and the amount of metastable austenite appearing in the formed coating (table 2).

In alloy-treated structural steels, and also in corossion-resistant steels of martensite class the temperature of the beginning of martensite transformation T_M *is* ranging within 550 ... 700 K (steel group №1, tabl. 2). Whilst wires made of these steels spraying it was found that the volume content of metastable austenite has reached 24%, if the temperature of wire heating is not higher than 2000 K.

The temperature of martensite transformation T_M in tool (die) steels, and also in structural spring steels is ranging within 420 ... 540 K (steel group №2, tabl. 2). Whilst wires made of these steels spraying it was found that metastable austenite appeared of amount 15 ... 25 об. % was possible if the sprayed wire was heated to the temperature not higher than 2100 K.

In corrosion-resistant and heat resistant steels as well as in Hadfield steel the temperature of martensite transformation T_M ranges from 70 ... 110 K (steel group №3, tabl. 2). Due to the low temperature of the beginning of martensite transformation T_M, the austenite structure in these steels is characterized by high resistance, hence they are called - «steels of austenite class». For the phase strengthening of the upper layers of steels of austenite class due to the process of martensite transformation a high degree of deformation is required, which is inaccessible at frictional interaction with lubricating material (boundary friction). It was found, that due to the wires spraying made of these steels at the temperatures above 2500 K it is possible to raise the temperature of martensite transformation T_M, the temperature of deformation $\gamma \rightarrow \alpha$ transformation $M_Д$ and carry out the destabilization of austenite phase in the formed coatings.

Table 2

The content of metastable austenite in the coatings obtained by spraying of different grades of steel

№ of steel group	Steel grade	Temperature of martensite transformation T_M, K	Temperature of heating at spraying, K	Austenite content in the coating, vol.%
1	09GC, 40KhN, 20Kh13, 40Kh13	550…700	1700…2000 2100…2500 > 2600	17…25 7…15 < 6
2	9KhC, Kh12MF 9Kh12, Kh6VF, 35KhNM, 40KhFVA, 65G	420…540	1700…2100 2200…2500 > 2500	15…25 8…12 < 6
3	08Kh18N10T 12Kh18N10T 110G13	70…110	1700…2000 2000…2500 > 2500	95…98 90…95 90…95

The austenite stability decrease in the third group steels coatings obtained by the spraying at temperature above 2500 K can be explained in the folowing way. The chromium and manganese content in steel has made the most important impact on the tempearture interval state of martensite transformation. Thus, the mangenese content decrease from від 5% to 1% has caused the raise of temperature T_M from 270 to 470 K [5]. As a result, one of the possible ways to increase temperature T_M is lower content of chromium or mangenese in the austenite phase of steels due to oxidation under spraying conditions. The change of the coating composition due to the intense oxidation at temperature above 2500 K has made possible to of austenite structure resistance and to raise temperature $M_Д$ to the roomtemperature level.

At wire spraying from steel of the first two groups of steel the preservation of great amount of metastable austenite can be explained in the folowing way. High speed of steel particles crystalization during the sprayed layer formation and slower speed of its cooling in the interval of martensite and bainite transformations under coating cooling conditions have provided the austenite thermal stabilization. The thermal stabilization is getting more intense if the reconditioned surface of the part is preheated. The increase of of metastable austenite contens was being obsderved at the reconditioned surface of the part heating to 480 K (fig. 4). Further heating of the part was resulted in decresae in strength of the coatings adherence with the reconditioned surface. Preheating of the part prior to the sparying of alloyed wire steels of high tempearture T_M has enhanced the effect of austenite stabilization and has made possible to increase the meatstable phase volume in the sprayed coatings.

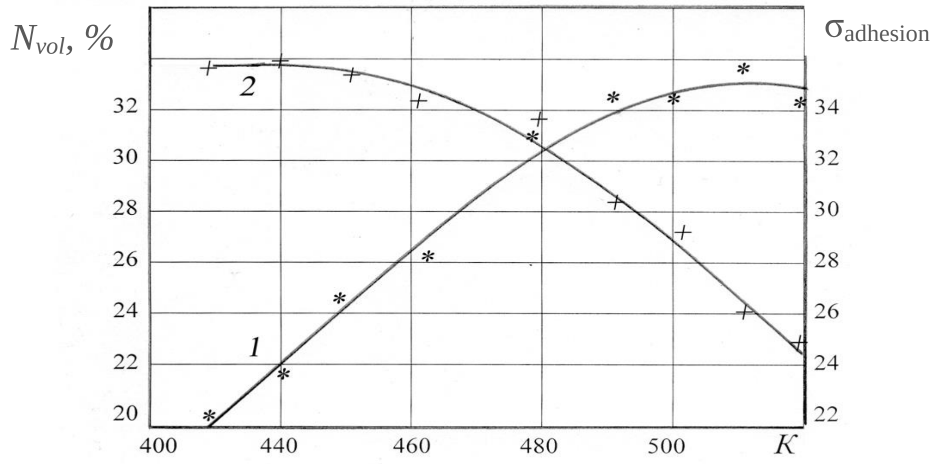


Fig. 4. The dependence of the amount of metastable austenite (vol.%) (1) in steel coatings 2Kh18N10T and 40KhN and their adhesion (MPa) (2) on the preheating temperature of the recoverable surface

Practical use of the study results

Some technological recommendations on transportation means parts reconditioning have been developed on the basis of the results of conducted study. Thus, the method of electric arc spraying using steel wire 40Kh13 was chosen to restore the worn out bearing spindles of distributing shafts. Wear resistance of reconditioned surfaces with coatings after the period of wear-in was 40 - 50% higher than the coating wear resistance sprayed by the same material by gas flame method. The analysis of development and operation testing results has shown that the reconditioned surfaces of distributing shafts of transport means with the coatings applied by electric arc spraying had the wear resistance 1,4 - 1,7 times higher than the coatings obtained due to the gas flame method.

Conclusions

The effect of anomalously great amount of residual austenite (20 - 40 vol.%) formation in gas thermal coatings of sprayed steels of martensite class has been determined.

It was proved that to provide the formation of metastable austenite with low temperature of deformation $\gamma \rightarrow \alpha$ transformation corresponding to the operating temperature of sliding friction units in the structure of sprayed coatings made of alloy-treated structural, instrumental and corrosion resistant steels, one should reach the determined conditions of the coating formation (heating temperature, the temperature of wire spraying, speed of melted particles cooling and the degree of their oxydation).

On the basis of conducted investigation some technologies have been proposed dealing with the parts of transportation means reconditioning by multifunctional coatings applying where the choice of wire heating method under spraying conditions is made depending on the temperature of the wire material martensite transformation start.

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Лопата В.М., Черновол М.І., Солових Є.К., Дудан О.В. Використання структурних аномалій в стальних газотермічних покриттях при підвищенні їх зносостійкості

Досліджена структури газотермических покриттів із дротяних матеріалів шляхом визначення раціональних методів керування процесом структуроутворення для досягнення найбільш високих фізико-механічних властивостей відновлюємих поверхонь деталей транспортних засобів. Встановлено ефект утворення аномально великої кількості залишкового аустеніту при напиленні покриттів із сталевих дротів. Запропоновано технології використання «аустенітного ефекту» для підвищення зносостійкості покриттів.. Визначено, що основними факторами, що впливають на вміст залишкового аустеніту в загартованій сталі, є швидкість охолодження сталі, концентрація легуючих елементів в аустенітній фазі, а також термічна стабілізація аустеніту при самовідпуску.

Показано, що для забезпечення формування в структурі напилених покриттів з легованих конструкційних, інструментальних та корозійностійких сталей метастабільного аустеніту, що має низьку температуру протікання деформаційного гама-альфа перетворення, яка відповідає температурам експлуатації вузлів тертя ковзання, необхідно досягнення певних умов формування покриття (температури нагріву і розпилення дроту, швидкості охолодження розплавлених частинок і ступеню їх окислення). Однією з найбільш ймовірних причин появи «аустенітного ефекту» в покриттях є розігрівання поверхневого шару до температури, що сприяє термічній стабілізації аустеніту, а також насиченню крапель розплаву легуючими елементами (перш за все хромом) і домішками впровадження (вуглець, азот) в процесі розплавлення дроту в полум'ї. Відносно низька швидкість польоту розплавлених частинок стали і висока концентрація пропану, що містить вуглець в продуктах горіння, сприяють глибокого насиченню крапель розплаву вуглецем. Ймовірно, що саме з цими обставинами пов'язаний високий вміст залишкового аустеніту в покриттях, отриманих газополуменевим напиленням. Додатковим фактором, що збільшує стійкість аустеніту в напиленому покритті може бути насичення крапель розплаву вуглецем в процесі розплавлення і розпилення з використанням полум’я пропану.

Проведені дослідження дозволили припустити, що як для методу газополуменевого напилення, так як і для методу електродугового напилення існують такі режими і сталі для розпилення які дозволяють забезпечувати формування в покриттях великої кількості метастабільного аустеніту, який в процесі роботи трибоспряження перейде в мартенсит. .На підставі проведених досліджень запропоновані технології відновлення деталей засобів транспорту шляхом нанесення багатофункціональних покриттів, в яких вибір методу нагріву дроту при розпиленні здійснюється в залежності від температури початку мартенситного перетворення матеріалу дроту.

Ключові слова: електродугове напилення, газополуменеве напилення, зносостійкість, залишковий аустеніт, відновлення, газотермічні покриття

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The selection and development of tribological coating

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Abstract

The strategy and methodology for selecting of optimal surface treatment for a given tribological application are the main objectives of study. The classification of main methods of coating processes and surface modification is given. The scheme of development of operation technology of surface treatment and coating deposition is proposed. The main initial data: the structure of tribological system (TrS); individual properties of TrS parts; lubricant properties; method of lubrication of TrS parts; properties of surrounding environment; external influences on TrS; technological limitations on TrS parts treatment; managerial and economical limitations. The selection of surface technology method is including the next successive steps: the preliminary analysis of TrS part interaction; development of models of friction and wear process of TrS parts; the choice of rational values of parameters of surface layers of TrS parts; the choice of rational composition and structure parameters of surface layers of TrS parts; the choice of rational technological route and methods of surface treatment of TrS parts; the experimental examination of surface strengthened materials and TrS and correction of surface treatment technology.\

Key, **words**: coatings, friction pair solid surfaces contact, surface engineering, tribological system

Introduction

The use of surface engineering methods in tribological applications is growing and will continue to grow as evidenced by a literature survey [1-9]. Surface treatment as coatings and films deposition and modification of surface layers can offer certain economic and technical advantages over the use of materials without the surface strengthen treatment. Their main advantage is that strengthen surface layers allow the base material of tribological system (TrS) parts to be optimized for strength purposes while the surface layer is optimized for reducing wear and increasing corrosion resistance, promoting film lubrication, enhancing lubricant effectiveness, modification surface function, etc. Furthermore, replacing the surface layer by coating deposition during repair may be more cost effective than new TrS part manufacture. But the principal disadvantage in using coatings concerns the possibility of separation from the base material of TrS part during use. While the discussions to follow emphasize the considerations important in the selection of tribological surface treatment, it should be noted that other alternatives might exist for any particular problem. This could involve, for example, use of a more effective lubricant, or a redesign of the tribological system elements, use of more effective methods of lubrication, development of new or use of improved materials, etc.

Classifacation of surface engineering methods

Many technological methods and processes of surface engineering are available for the modification of surface characteristics. Tribological surface treatment methods are used for different purposes: 1. Replace surfaces by coatings and films deposition; 2. Surface modification (surface alloying and/or microstructure is altered); 3. Combination of methods for coating deposition and surface modification. A wide variety of surface modification methods are available for tribological purposes. The main categories are: 1. Modification of surface layers in process of shaping processing; 2. Heat (volume) treatment; 3. Surface heat treatment; 4. Treatment by surface plastic deformation; 5. Surface thermomechanical treatment; 6. Surface alloying; 7. Chemical and thermochemical treatment, including microarc oxidization; 8. Ion implantation; 9. Formation of surface layer composite structure by introduction of hardening phase particles; 10. Others and hybrid methods.

Resurfacing essentially replaces surface layer of base material (or previously deposited coating) with another having presumably more desirable friction and wear properties. Usually the new surface is harder than the surface replaced but not always. A wide variety of coating compositions is available. Each of these compositions can be applied by a variety of processes. The main categories of coating deposition processes are: Electroplating; Electrophorus; Electroless plating; Welding; Thermal spraying; Physical Vapor Deposition; Chemical Vapor Deposition (CVD); Immersion on melt; Electro-spark alloying; Electro-magnetic alloying; Bonding of powder layers; Solid phase plating (bonding of plates); Painting; Continuous deposition of films in process of friction (rotaprint, from environment, etc.) ; Others.

Some of these application processes are very simple and inexpensive such as painting. Others are very complex either requiring vacuum processing or requiring a series of treatments and pretreatment. Some of them can be applied in the field while others can only be applied at particular facilities. There is no shortage of tribological coatings and surface layers to try for almost any need. The primary problem that exists is knowing what surface treatment to select for any given application. A related problem is that surface treatment developers often do not know where their coatings should be used or what coating or kind of surface modification to develop to meet a particular need. There is a need for a strategy or methodology for selecting a surface layer composition and structure and methods of their obtaining for a given tribological application. In this paper such a strategy is proposed and elements of that strategy are discussed.

Sold surface characteristics

The difficulties of selection of surface treatment methods are connected with very large number of parametric variables of solid surface quality, which could be described by next ensemble of characteristics

$$K \supseteq G_{ex} \cup G_{in} \cup S_c \cup S_s \cup Ph_c \cup Ph_s \cup Ch_c \cup Ch_s \cup Df_c \cup Df_s \cup St_c \cup \\ \cup St_s \cup Pmp_c \cup Pmp_s \cup Ptp_c \cup Ptp_s \cup ...., \quad (1)$$

where G_{ex} is ensemble of characteristics, which are characterized the geometry parameters of external surface of strengthened layer and in its turn could be characterized by ensemble $G_{ex} \supseteq G_{exw} \cup G_{exm}$;

G_{exw} and G_{exm} are ensembles of parameters of waviness and roughness of surface correspondingly;

G_{in} is ensemble of parameters, which are characterized the geometry parameters of internal surface of strengthened layer (or coating) and in its turn could be characterized by ensemble $G_{ix} \supseteq G_{ixw} \cup G_{ixm}$;

S_c and S_s are ensembles of parameters, which are characterized the geometry configuration inaccuracy of surface of strengthened layer (or coating) and its interface with main material correspondingly;

Ph_c and Ph_s are ensembles of parameters, which are characterized;

Ch_c and Ch_s are chemical composition; St_c and St_s are ensembles of parameters, which are characterized the structure; Df_c and Df_s are ensembles of parameters, which are characterized the deformation;

Pmp_c and Pmp_s are ensembles of parameters, which are characterized the physico-mechanical properties; Ptp_c and Ptp_s are ensembles of parameters, which are characterized the thermophysical properties; indices c and s are for strengthened layer (or coating) and structure of near-surface layer of main material and/or transition zone respectively.

For search of optimal solution of particular tribological problem it is necessary to manifest the ensemble of parameters, which characterized the assembly and friction surface working conditions

$$TrS \supseteq E \cup C_e \cup L_e \cup F \cup M_e \cup W_e, \quad (2)$$

where E is ensemble of characteristics of TrS work pieces;

L_e is ensemble of characteristics of linking between work pieces;

F is ensemble of kind of friction and its main characteristics;

M_e is ensemble of mutual shifting of TrS work pieces;

W_e is ensemble of wear characteristics of TrS.

For dataware of choice of surface treatment method it is necessary to elaborate the ensemble of parametric variables of solid surface quality, which influenced on wear-resistance at different kinds of wear and recommended for control of wear-resistance

$$QPSS_i \supseteq G_{exi} \cup G_{ini} \cup S_{ci} \cup S_{si} \cup Ph_{ci} \cup Ph_{si} \cup Ch_{ci} \cup Ch_{si} \cup Df_{ci} \cup Df_{si} \cup St_{ci} \cup \\ \cup St_{si} \cup Pmp_{ci} \cup Pmp_{si} \cup Ptp_{ci} \cup Ptp_{si} \cup ...., \quad (3)$$

where index mark “i” is given for certain kind of wear. \

Furthermore, it is necessary to elaborate the ensemble of parametric variables of solid surface quality, which possible to control at each method of surface treatment and to determine the limits of these control.

$$QPSS_j \supseteq G_{exj} \cup G_{inj} \cup S_{cj} \cup S_{sj} \cup Ph_{cj} \cup Ph_{sj} \cup Ch_{cj} \cup Ch_{sj} \cup Df_{cj} \cup Df_{sj} \cup St_{cj} \cup \\ \cup St_{sj} \cup Pmp_{cj} \cup Pmp_{sj} \cup Ptp_{cj} \cup Ptp_{sj} \cup ...., \quad (4)$$

where index mark “j” is given for certain kind of surface treatment.

Methodology surface engineering methods selection

Coating deposition and surface modification have rapidly evolved in recent decades from simple and traditional methods to extremely sophisticated technologies. These developments are part of an effort to eliminate the limitations imposed by oil-based lubrication and the process of an effort to eliminate the limitations imposed by oil-based lubrication and in the process are changing the general perception of the limits of wearing contacts [6]. Knowledge of the mechanisms behind these improvements in lubrication and wear resistance is, in most cases, very limited. The methods employed in most studies on surface coatings and modification are empirical and there is relatively little information available on which surface technology is the most suitable for a particular application. Prior to selecting the coating material and technological method it is necessary to determie the prime objective which could or be to reduce friction or suppress wear or both. During the selection of the most effective surface material and process to supress wear in a particular situation, the prevailing wear mechanism must first be recognized and assessed.

In the last years, a lot of research is being carried out in field of tribological coatings and surface treatment, and although they are being increasingly used in practice, little is still known about their properties and their tribological behaviour, especially for new advanced surface technology. Different types of coatings of the same composition have different mechanical and tribological properties, depending mainly on the type of deposition process and substrate material. Furthermore, due to the specific test methods and conditions for given applications or research facilities of an organization, it is seldom possible to compare the results obtained by different researches. Selection of a coating-material and coating-process combination for a specific substrate can be complex. There are a great number of possible combinations, not all of which lead to satisfactory solutions [1,6-9]. To overcome these problems, the strategy and methodology for selection of optimal tribological coatings and surface treatment for a given application are proposed.

The selection of types of surface strengthen treatment include following stages as shown on figure 1:

1) study of initial data including: composition and internal relations of TrS (parts; relations between them; lubricant; surrounding environment); individual properties of TrS parts including geometry parameters of parts and friction surfaces (macro- and micro-geometry) and properties of main material; lubricant properties (volume and surface properties, chemical and physical, etc.); aggregate properties of lubricant and TrS parts (adsorption properties, moistness, etc.); lubrication manner influencing at first on techniques and lubrication type; properties of surrounding environment (chemical composition, corrode influence, humidity, temperature, pressure, etc.); external influences on TrS (kinetic – sliding (rolling) velocity V, hydrodynamic velocity; dynamic – mechanical force, pressure P, electric field parameters; thermal – temperature ϑ_o, thermal flow, thermal gradient); technological limitations on TrS parts treatment (shape and sizes of parts and surfaces, materials, variability of properties, technological heredity, etc.); managerial and economical limitations (required productivity, presence of equipment, materials, energy sources and others, sanitary, hygienic and ecological demands, permissible expenses, etc.);

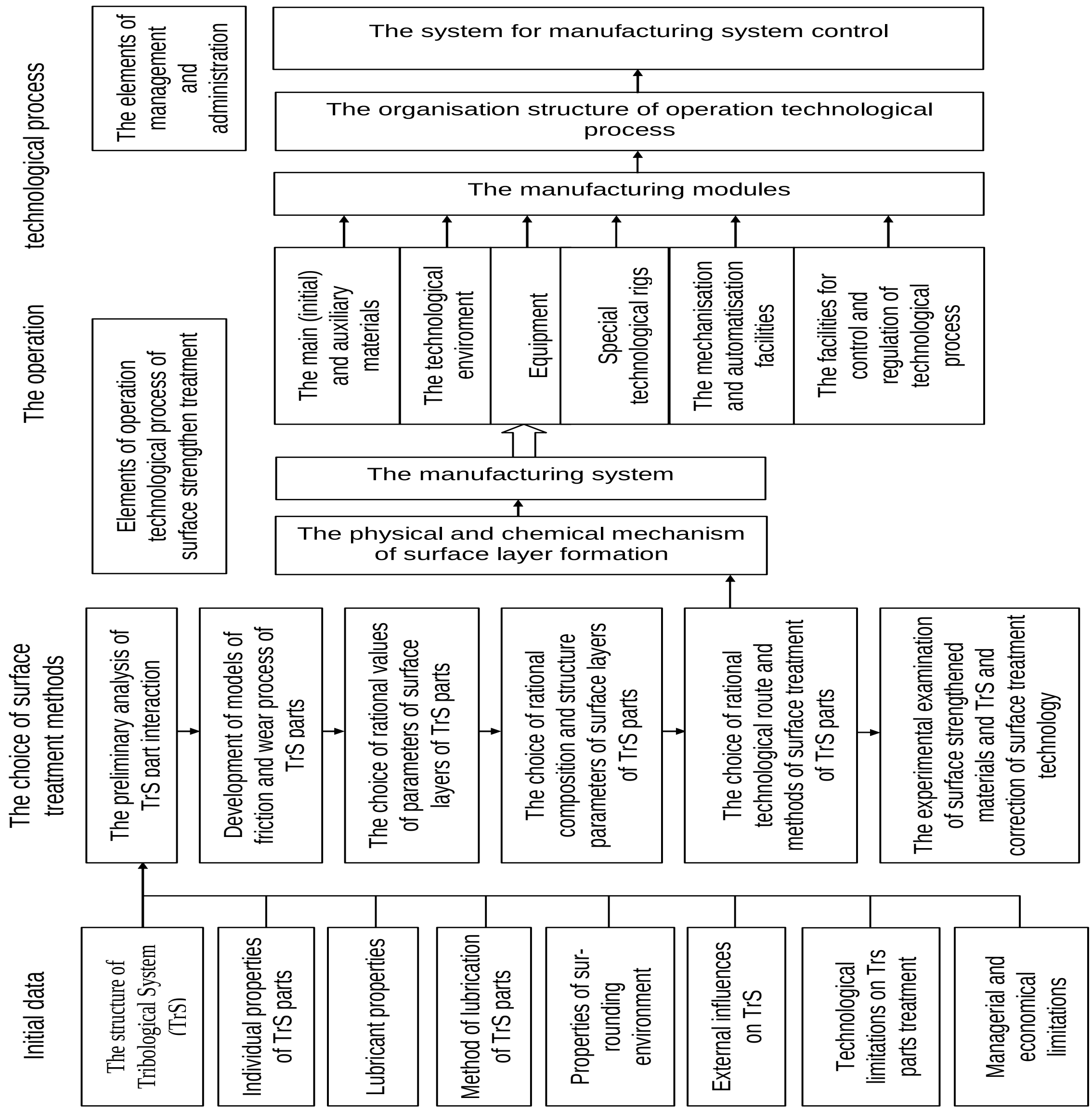

Fig. 1. Scheme of development of operation technology of surface strengthen treatment

2) determination of TrS parts interaction at static and dynamic conditions (adhesion, adsorption, chemosorption, oxidation, corrosion, diffusion, elastic strain, plastic deformation, microcutting, scratching, structure and phase transformation, etc.);

3)\development of scheme of TrS action, including preliminary determination of TrS characteristics for describing of input values X transformation in output values Y

$$\{X\} = \{P, V, \vartheta_o\} \Rightarrow \{Y\} = \{F_t, Z, P_t\}, \quad (5)$$

where F_t is friction resistance, Z is wear and seizure, P_t is accompany processes.

(1) development of models of friction and wear process of TrS parts (physical, mathematical, imitative, analogue);

(2) determination of rational values of parameters of surface layers properties by using models of friction and wear (by obtaining of permissible values of Y);

(3) selection of rational composition and structure of surface layer of TrS parts (it must take into account existing analogues and also structure – properties correlation's);

(4) determination of direction of surface strengthen treatment of friction surface of TrS parts: or surface layers modification, or coating deposition or their combination;

(5) determination of list of possible physic-chemical methods of surface strengthen treatment;

(6) preliminary selection of optimal methods of surface strengthen treatment by using elected criterions of optimisation and maintenance of demanded technique-economical limitations;

(7) experimental test of surface strengthen treatment in laboratory or empirical-industrial conditions;

(8) preliminary projection of operation methods of surface treatment – equipment, special technological rigs, technological variables, technological environment, the facilities of mechanisation, robotisation and automatisation, methods of management and control, technico-economical comparison of operation variants;
(9) clarification of relationships between operation technology of surface strengthen treatment and manufacturing procedure of TrS parts production; correction of structure for both processes for purpose of their optimisation;
(10) final selection of surface strengthen treatment methods, development of measures for reliability of maintenance of demanded characteristics of technological process; development of project of processing system of surface treatment.

The selection of optimal methods of surface strengthen treatment usually realizing by using of technical criterions as securing of TrS tribotechnical characteristics accordance to demanded one (figure 2).

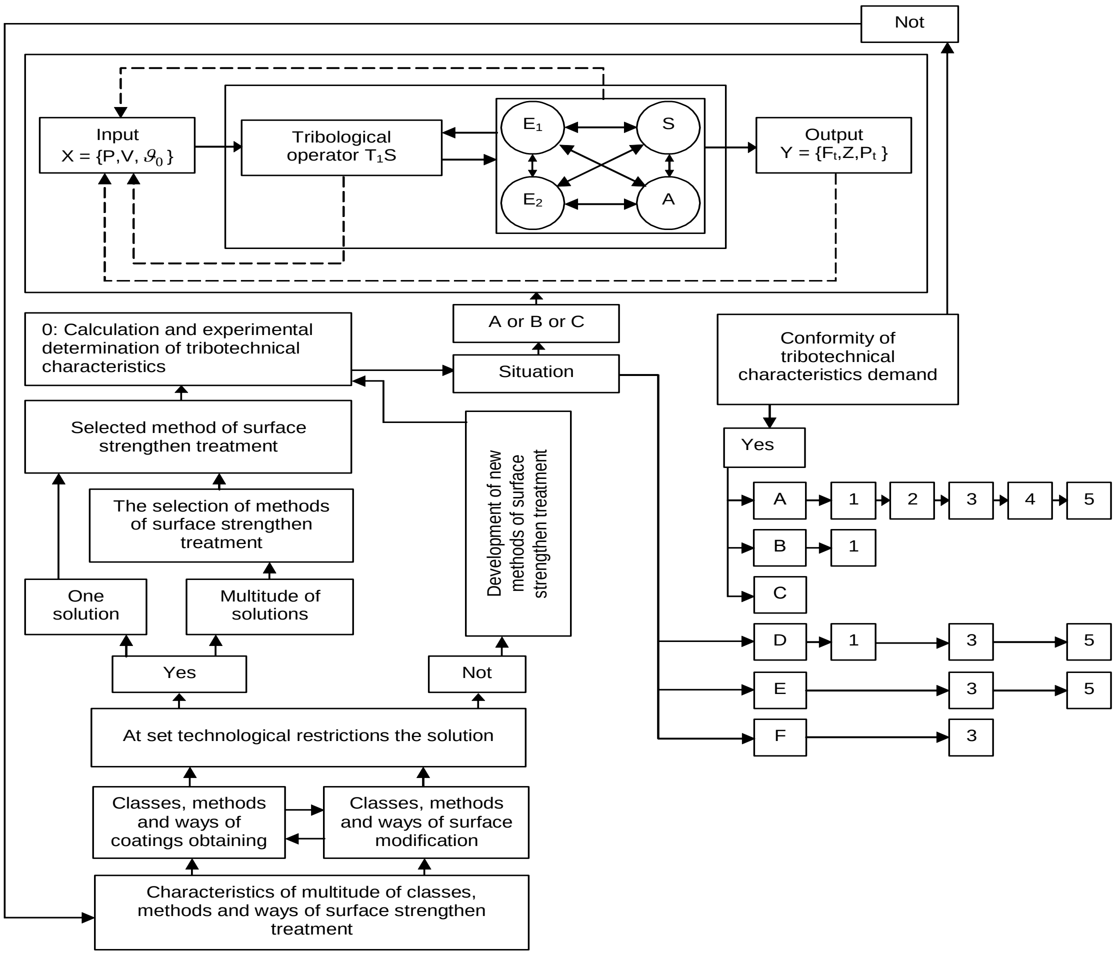

Fig. 2. Scheme of selection of optimal methods of surface strengthens treatment.
Situation: A – development of tribological system not having analogues; B – selection of new friction pair for instead out-of-date one; C – selection of friction pair for weak-loaded typical tribological system; D – improvement of typical tribological system; E – replacement of friction pair by new serial one; F – determination of inter-repair cycle. Stages of selection: 0 – calculation and experimental determination of tribotechnical characteristics; 1 – research test at determined parameter; 2 – boundary research test (at extremes conditions); 3 – model research test; 4 – defined nature test; 5 – exploit test

In case of presence some equivalent surface treatment variants on tribotechnical characteristics for the final selection is used economical criterions. The system of selection of optimal surface strengthen treatment are including the scheme of TrS action and database of multitude of surface strengthen treatment classes and methods characteristics. Preliminary by using technological limitations, other initial data and data base one could select a recommended groups of parameters of surface layers quality which promoted the wear resistance increasing. The next would be the selection of respective methods of surface strengthens treatment, which allowed the control of desirable parameters of surface layer quality. Then by use of early developed model of friction and wear for the this TrS is making more detailed valuation of selected decision including calculation and experimental determination of tribotechnical characteristics and following test of TrS. The use of different methods of surface strengthen treatment is opening the vast possibilities of control of friction surfaces contact interaction independently from composition and structure of main materials of TrS parts.

Depending on kind of aggregate of contacting surface layers of friction pairs it is possible to divide them on three classes: 1) contact of two one-phase surface layers; 2) contact of one-phase layer and composite structure surface layer; 3) contact of two composite structure surface layers.

Only in case of contact of one-phase surface layers the common number of possible variants of contacts is very high and could be evaluated by next equation

$$K_{sum} = 2(n^2 + m^2 + q^2) - 3(n + m + q) + 6 + 2(nm + nq + mq) \tag{6}$$

where n is a number of simple substances, m is a number of two- and many-component solid solutions, q is a number of two- and many-component chemical compounds.

Those multiplicity of possible variants of contact in case of only one-phase surface layers is allowed by choice of composition of surface layers materials and their structure to control the quality of physical contact of friction pairs, in particular the size of real contact area, inclination to forming of desirable secondary structures in process of friction, properties of third (intermediate) substance, fatigue wear resistance, etc.

In reality the factual variety of possible contacts of one-phase layers is considerably more inasmuch as the friction processes depends not only from chemical composition of contacted surface layers, but also from their structure and energetic parameters, including size, shape and character of mutual orientation of grains; structure and strength of intercrystalline boundaries; the level of strain hardening; type of crystal lattice; mechanical properties; surface properties, etc.

The creation on one or both friction surfaces of layers with composite structure lead to essential increasing of possible variants of friction surfaces contacts and to appearance of some new physic-chemical phenomena in process of friction. The peculiarities of contact interaction of such friction pairs at first connected with simultaneous presence of contact aggregate between friction surfaces. But the description of friction zone in contact of such surface layers is demanding the use of complex of special parameters.

Conclusion

The approach to the development and selection of surface strengthen treatment for tribological purposes have to involve methods of system analyses. The tribological system work-pierces and friction surfaces functions must be accurately defined in functional, technological, economical, ecological and other respects. The proposed strategy has the potential for simplifying selection and design of coatings and/or surface layers and reduction of development time for new tribological systems and/or improvement of existing ones. But the subsequent laboratory tests at several levels must be also completed. Development of computer modeling methods for selection of surface engineering processes and experts systems for developing of surface engineering technology for particular application is necessary. The system approach could be also useful for development of new tribological coatings and surface modification methods. However a lot has still to be done for development of methodology of selection of optimal methods of surface engineering and their improvement.

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Харламов Ю.О., Лопата Л.А., Брусило Ю.В., Головащук М.В. Вибір і розробка трибологічного покриття

Стаття присвячена стратегії та методології вибору оптимальної поверхневої обробки для деталей вузлів тертя. Дано класифікацію основних методів нанесення покриттів та поверхневої зміцнюючої обробки. Запропоновано схему розробки операційної технології поверхневої обробки та нанесення покриттів. Основними вихідними даними є:

- структура трибологічної системи (TrS); індивідуальні властивості елементів TrS;

-властивості мастильного матеріалу; метод змащування TrS; властивості довкілля; зовнішні дії на TrS;

- технологічні обмеження на обробку деталей TrS;

- організаційні та економічні обмеження.

Вибір методу поверхневої обробки здійснюється виконанням наступних послідовних етапів:

1) попередній аналіз взаємодії деталей TrS; \

2) розробка моделей процесів тертя та зносу деталей TrS;

3) вибір складу, структури та раціональних значень параметрів поверхневих шарів деталей TrS;

4) вибір раціонального маршруту та методів поверхневої обробки деталей TrS;

5) експериментальна перевірка поверхнево зміцнених матеріалів та TrS та подальше коригування технології поверхневого зміцнення.

Ключові слова: покриття; контактна поверхня пары тертя, інженерія поверхні; трибологічна система