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Computational studies of stuffing box packing seal wear mechanism using the Archard model

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Abstract

The wear model of the stuffing box packing seal, particularly the surface of the protective sleeve of the shaft, is presented. Modeling was performed using the ANSYS software, using the Transient Structural module which have the built-in Archard wear model. The wear model was validated in accordance with the results of previous experimental studies considering the effect of applied pressure. It was determined that when the degree indicators in the Archard equations are m = 1.5 and n = 1.3, the proposed wear model allows obtaining sufficiently accurate wear intensity values. The values of relative wear for different materials of protective sleeves are compared. Graphs of the contact pressure distribution along the width of the friction pair at different values of the applied pressure and linear rotation shaft velocities are given. The results of the shaft surface shape change due to the loss of material were obtained. The resulting change in shape is considered idealized, since this study does not consider the presence of abrasive inclusions in the medium, uneven pressure distribution on the packing gland, temperature changes, etc. However, this study can be useful in predicting the wear of the main components of the stuffing box packing seal.

Key words: wear, Archard model, stuffing-box packing seal, contact pressure distribution, material volume loss.

Introduction

The wear of stuffing box packing seals is a long-standing problem in mechanical engineering, because of the dynamic behavior, they are subject to various tribological interactions, such as friction, wear and corrosion. This can significantly affect the service life. Thus, solving the problem of the wear of packing seals is of great importance for increasing the reliability and efficiency of centrifugal machines.

The peculiarity of the stuffing-box packing seals work is that during the service life the surface of the packing does not have time to undergo a direct process of wear. In the process of operation, it gradually loses its sealing properties: it decreases in size under the influence of the applied pressure and the packing gland, due to which the clearance between the packing and the shaft increases; the impregnation of the packing is washed out, due to which the friction coefficient increases, and as a result, this is accompanied by an increase in heat generation. Thus, the replacement of the packing ring is performed before its fibers are rubbed.

Therefore, it is the shaft or the protective sleeve of the shaft that undergoes direct wear in the stuffing-box packing seal. And therefore, the amount of wear of the surface of the shaft or sleeve, as in the case of [0], can be determined experimentally by weighing.

Literature review

Currently, research is being actively conducted on the calculation of the service life of mechanical seals, since they are widely used for centrifugal machines sealing. The main parameter in determining the durability of sealing elements is the degree of wear of the contact pair surfaces. Firstly, researchers are focused on the study of the wear of seal surfaces under the influence of various parameters for each individual case. For example, the influence of temperature deformations [0], taking into account the combined abrasive and adhesive wear [0], taking into account the uneven wear of surfaces [0], the influence of contact state that changes over time [0], or the effect of elastohydrodynamic lubrication [0-0]. The choice of materials for the friction pair is also analyzed, in particular based on carbon, which significantly affects the service life of the seal [0, 0].

Stuffing-box packing seals are one of the types of mechanical seals. They play a key role in various engineering systems, where reliable sealing of liquids is required. These seal designs are installed in centrifugal machines and prevent leakage of liquids or gases, ensuring the tightness of the system. The importance of the durability of these seals cannot be overstated, as any failure can lead to leakages, increased maintenance costs and environmental issues.

Although previous research has made significant progress in understanding wear mechanisms and its modeling in mechanical seals, there remains a notable gap that applies to stuffing box packing seals. Most likely, this is due to a significantly lower resource of packing seals compared to traditional mechanical seals. Therefore, this direction of research has prospects, since new modernized designs of radial and face packing seals are being created [0]. These designs are characterized by an increased service life. Therefore, the creation of a wear model of the stuffing box packing seal can contribute to increasing the service life of the seals.

Previous studies have demonstrated the importance of wear modeling in understanding and predicting contact pair wear. Computational tools such as finite element analysis (FEA) and computational fluid dynamics (CFD) are used to model wear behavior in mechanical seals. In general, when solving wear-contact problems, most researchers rely on the Archard wear model, including studying wear in mechanical seals. In our case, ANSYS software stands out as a reliable computational tool that offers the ability to simulate wear based on Archard's wear law and predict its effect on seal performance.

The Archard wear model, proposed by Archard in 1953, is the fundamental basis for predicting wear in tribological systems. This model quantifies wear as the proportional loss of material volume due to sliding or relative movement between surfaces. The Archard equation (1), which includes the wear coefficient (K), the applied load (P), and the sliding distance (S), is widely used to predict the wear volume loss. The simplicity and versatility of this model make it a valuable tool for wear analysis, especially in seals.

$$W = K \times S \times P \tag{1}$$

The current study is aimed at providing information on the wear rate of the contacting surfaces of stuffing-box packing seals, focusing on the numerical modeling of this phenomenon in a centrifugal pump. However, it does not include taking into account the features of manufacturing and metalworking of individual sealing components or comprehensive experimental verification, which remain the object of further research.

Purpose

The purpose of this work is to create a computer model of the surface wear of the stuffing box packing seal, to compare the obtained results with the experiment, and to use this model to solve the wear-contact problem considering the Fluid-Structure Interaction (FSI) problem of the stuffing box packing. This model will make it possible to determine the contact pressure distribution more accurately when changing such parameters as the applied pressure and the shaft rotation speed. In addition, it is planned to investigate the change in the contact pressure distribution during the wear of the contacting surfaces, to determine the amount of wear and, as a result, the change in the shape of the shaft contact surface. The obtained results in general will make it possible to predict the resource of the main components of stuffing box packing seals more accurately. They will also become the basis for further design modernization of stuffing box packing seals.

1. Materials and methods

1.1. Validation of the radial stuffing-box packing seal wear model

In the ANSYS software, the modified Archard equation (2) is used, where $\dot{W}$ – wear rate, K – dimensionless wear coefficient, H – hardness of the material being worn, v – sliding speed, P – applied pressure.

$$\dot{W} = \frac{K}{H} \times v \times P \tag{2}$$

The most interesting is the wear coefficient K, which can be determined only as a result of conducting an experiment. So, at work [0] given values of wear intensity (mg/h), applied pressure (MPa), sliding speed – 3 m/s. The material of the protective sleeve is stainless steel, the hardness of which can be considered 1/3 of the yield strength (σ_y) [0]. For stainless steel, the value of the yield point is 207 MPa. Therefore, the value of hardness is equal to (3)

$$H = \frac{\sigma_y}{3} = \frac{207}{3} = 69 \text{ (MPa)} \tag{3}$$

Then, from equation (2), we can express the coefficient K (4), the values of which are given in table 1:

$$K = \frac{\dot{W}H}{vP} \quad (4)$$

Also, an important point in solving the wear problem is finding the correspondence between the experimental wear intensity (J) and the Archard wear rate ($\dot{W}$). The correspondence is given in formula (5):

$$\dot{W} = J\frac{10^{-6}}{\rho \cdot 3600}, \quad (5)$$

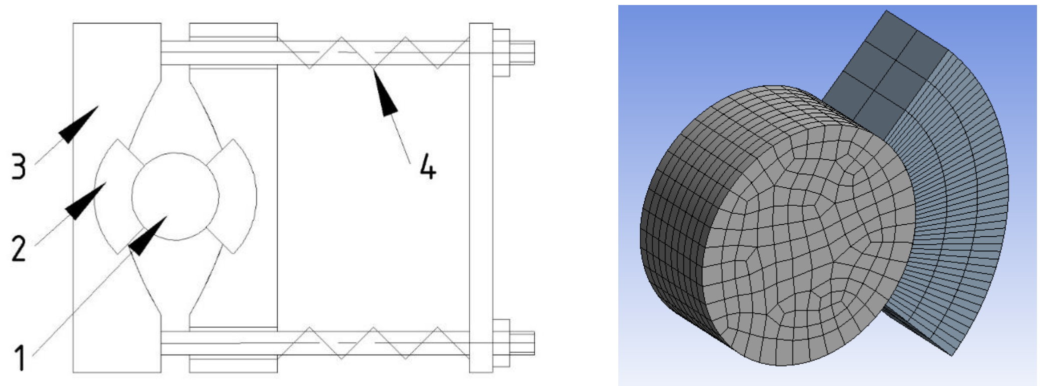
where ρ – the density of the sleeve material.

A three-dimensional model of the experimental rig was created for conducting investigations (Fig. 1) [0]. The rig consists of two pads 3, into which pre-pressed samples of stuffing box packing 2 are inserted. The samples are inserted in such a way that their position does not change during the rotation of the shaft with a protective sleeve 1. The shaft is driven into rotational motion by a motor that can change the rotation speed from 640 to 3200 rpm. The force of the applied compression is regulated by the compression of the springs (4) in the range of 10-150 N.

Table 1

Values of experimental wear intensity [0], wear rate and wear coefficient depending on the applied pressure

The intensity of wear (experimental) (mg/h)	Applied pressure (MPa)	Wear rate (experimental) ($m^3/s*10^{-14}$)	Wear coefficient (10^{-8})
0.21	0.08	0.752	0.706
0.67	0.12	2.401	1.503
0.93	0.17	3.333	1.472
2.44	0.25	8.746	2.627
3.68	0.34	13.190	2.910
7.00	0.46	25.090	4.096



a b

Fig. 1. Scheme (a) and three-dimensional model of the rig (b)

The model has two main components: a shaft with a diameter of 30 mm and a thickness of 13 mm, and a stuffing-box packing sample with a square cross section of 13x13 mm. Shaft material – stainless steel 30Ch13 (Young's modulus – 2.1 GPa, Poisson's ratio – 0.31), stuffing-box packing material – asbestos fluoroplastic AFT (Young's modulus– 50 MPa, Poisson's ratio – 0.45).

A frictional contact model was used to simulate wear. The contact surface is the surface of the sleeve, the surface of the stuffing box packing is the target surface. The coefficient of friction between the surfaces is 0.04. The contact problem was solved based on the Augment Lagrange formulation.

When creating a finite element mesh, it is important to determine the number of elements in both bodies. It is necessary to achieve a balance between accuracy and calculation time. The view of the finite element mesh is presented in fig. 1, b. The number of elements was equal to 4290, nodes to 22158.

The following boundary conditions are presented: external pressure applied to the surface of the stuffing box packing and the shaft rotation linear velocity - 3 m/s (Fig. 2). At the same time, both solid bodies are constrained to move along the y axis, and the shaft surface has the ability to rotate around its own axis of rotation.

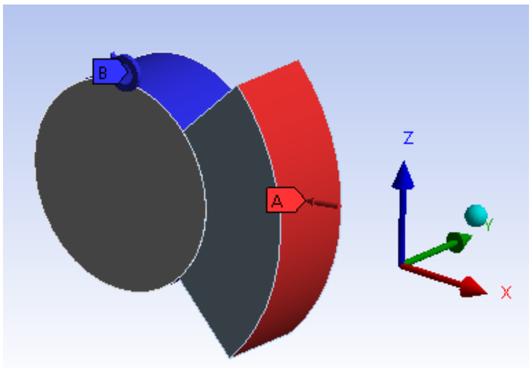


Fig. 2. Boundary conditions

To determine the wear of the shaft, the built-in command (6) was used, which uses the modified Archard formula (7). Where the coefficients *m* and *n* are degree indicators at pressure and velocity, respectively.

TB,WEAR,1,,,ARCD
TBDATA,1,K,H,m,n. (6)

$$\dot{W} = \frac{K}{H} \times P^m \times v^n. \quad (7)$$

In this study, it is assumed that the wear process occurs in the isothermal regime. This assumption assumes that the working medium flowing through the seal completely removes excess heat.

1.2. Wear of the shaft surface, considering the Fluid-Structure Interaction problem of the stuffing box packing

Determining the amount of shaft surface wear is very important for radial stuffing box packing seal. As is known, the highest level of wear is observed in the place of increased contact pressure in the friction pair. The рисунокwordcontact pressure in a face packing seal is considered. Here, in addition to the direct wear-contact problem, the FSI problem is additionally solved. A similar picture is characteristic of the radial stuffing box packing seal. In fig. 3 shows the effect of hydraulic pressure on the stuffing box packing. At the same time, part of the stuffing box packing from the applied pressure side is pressed against the surface of the shaft, and the other part at the exit from the seal is in contact with it. Therefore, in addition to contact forces, it is critically important to consider the action of hydroelastic forces to solve the wear-contact problem of the stuffing box packing seal. The algorithm flowchart for solving following problem is presented in fig. 4.

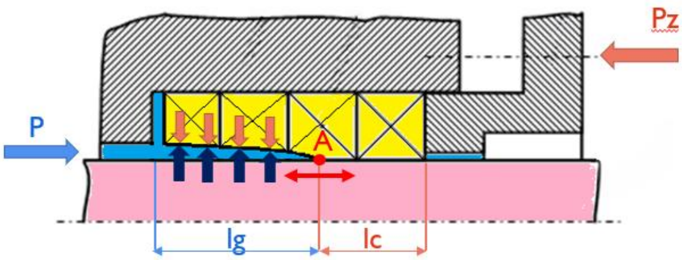


Fig. 3. FSI consideration in stuffing-box packing seal. P – applied pressure; Pz – pressure acting on the sleeve; lg – zone with a significant clearance; lc – contact zone; A – transition point between the zones, which changes its position along the package depending on the operating conditions

The simulation was carried out by changing the pressure of the working medium and the shaft rotation speed. The values of operating parameters are presented in Table 2.

Table 2

Operating parameters

Parameter	Value				
Applied pressure (MPa)	0.2	0.4	0.6	0.8	1.0
Linear velocity of shaft rotation (m/s)	1	2	3	4	5

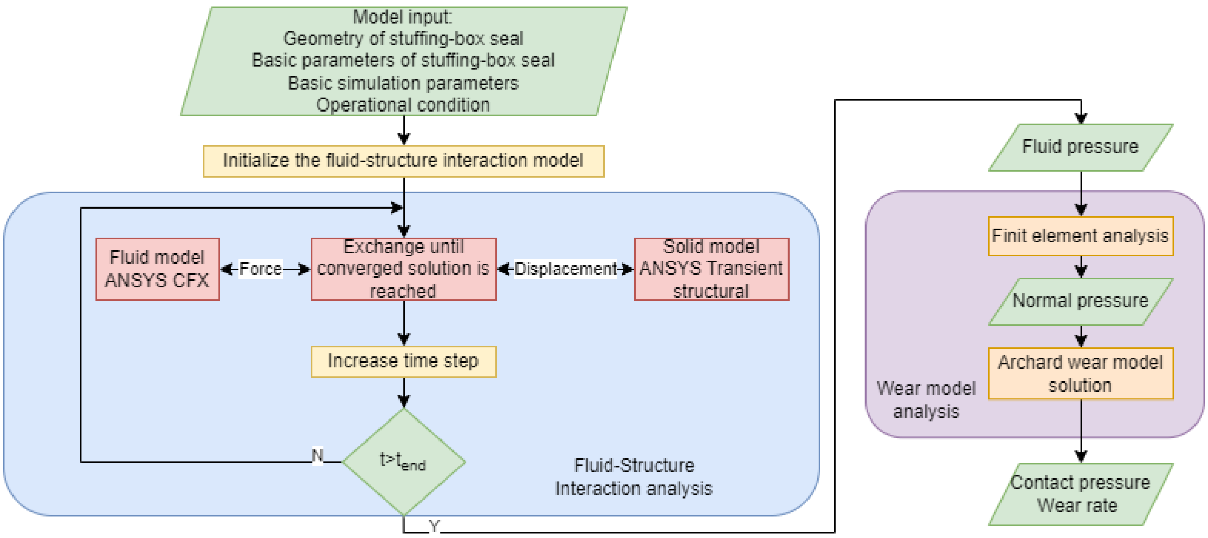


Fig. 4. Algorithm flowchart for solving the wear-contact problem of stuffing box packing seal

Results

2. Results of wear model validation

For the validation of the stuffing-box packing seal wear model, numerical studies were performed with different combinations of *m* and *n* degree indicators. In the result, it was determined that with the values of the degree indicators *m*=1.5 and *n*=1.3, the proposed wear model coincides with the experiment. The results of the research are presented in fig. 5, which shows the graph of the dependence of the volume loss rate on the applied load. The graph shows that the values of the wear volume at the corresponding loads, obtained during modeling, generally coincide with the experimental data. The deviation does not exceed 10%.

In addition, it should be noted that in work [0], the amount of relative wear of a sleeve made of different materials and with different hardening methods was also experimentally investigated. Since in this work there is no information about specific values of the hardness of the shaft, but only the difference in the intensity of wear is shown. Therefore, the hardness values were selected from reference literature [0]. A comparison of the results of simulation and experiment in the form of the relative wear for different materials of the shaft is shown in fig. 6. The unit was taken as the value of the relative wear indicator for the material of the shaft made of cast iron 18. After analyzing the obtained dependence, it can be concluded that although the values of relative wear for the calculation model are underestimated in comparison with experimental data, the tendency to decrease the amount of wear for different types of materials in the sequence shown in Figure 6.

Thus, it can be stated that Archard's model can be applied in studies of shaft wear in stuffing-box packing seals.

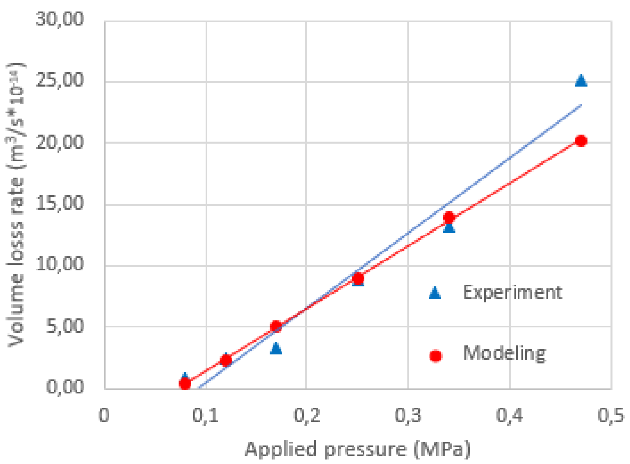


Fig. 5. Dependence of volume wear on the applied pressure

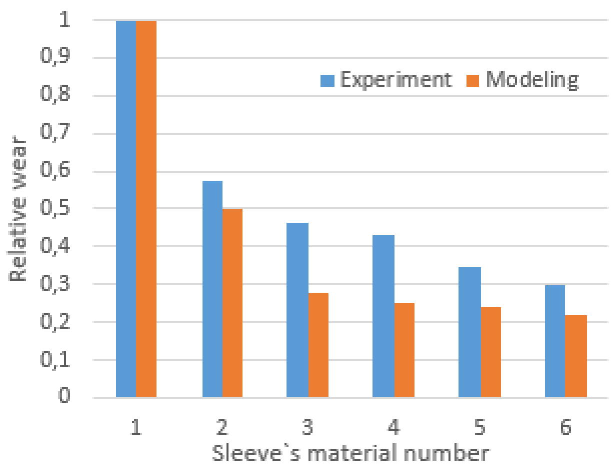


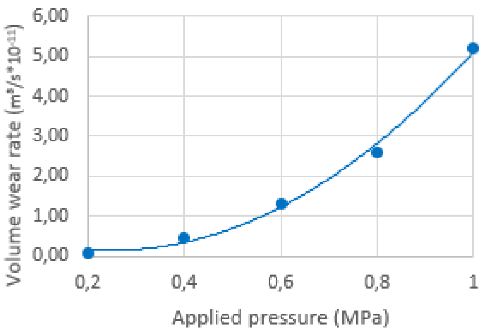
Fig. 6. Relative wear of sleeves made of different materials: 1 – cast iron 18; 2 – cast iron 18 with induction hardening; 3 – steel 40Ch with isothermal hardening; 4 – cast iron 18 with induction hardening and carburizing; 5 – steel 20 with nitriding; 6 – steel 45Ch

3. The results of solving the wear-contact problem considering FSI problem

The wear intensity and the contact pressure distribution along the width of the friction pair were chosen as the results of the study.

3.1. Wear intensity

As a result of the conducted study, the wear intensity of shaft was determined depending on the change in applied pressure (Fig. 7a) and the shaft rotation linear velocity (Fig. 7b). Thus, with a change in the shaft rotation linear velocity, there is a linear increase in the wear intensity. At the same time, with an increase in the applied pressure, the wear intensity increases according to a polynomial dependence. Such a discrepancy in dependencies is explained by the fact that when calculating the wear intensity when the applied pressure changes, the wear degree indicator also changes with the change in pressure**.**



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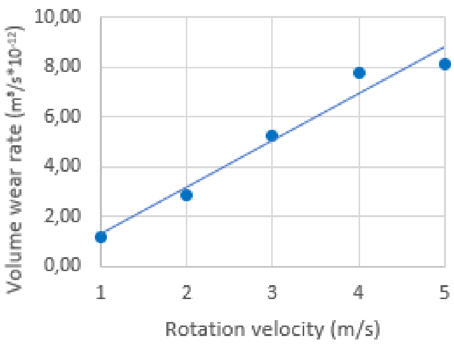


b

Fig.7. Dependence of the wear intensity on the applied pressure (a) and the shaft rotation linear velocity (b)

3.2. Contact pressure distribution

In fig. 8 shows the contact pressure distribution over the width of the friction pair at different values of the applied pressure. The point 0 mm along the width of the friction pair is the entrance to the seal, and the point 13 mm is the exit. It can be seen from the graph that as the applied pressure increases, the contact pressure also increases. The contact pressure increases when approaching the exit from the seal. This trend is explained by the fact that the hydraulic pressure decreases as it approaches the exit from the seal (Fig. 3).

In fig. 9 a-e show the contact pressure distributions before and after wear of the shaft sleeve. It can be seen from the graphs that after wear, the contact pressure decreases along the entire width of the friction pair. Moreover, when the applied pressure increases, the contact pressure drop also increases. Change (decrease) in contact pressure in the process of modeling is one of the indirect signs of wear of contacting surfaces.

The study of the effect of changing the rotation speed of the shaft on the distribution of contact pressure was carried out at an applied pressure of 0.4 MPa (Fig. 10). Analyzing the effect of changing the rotation speed of the shaft, it can be noted that there is no clear relationship between the increase or decrease of the contact pressure relative to the increase in the linear velocity of shaft rotation, which is quite well confirmed by the results of the experiment [0].

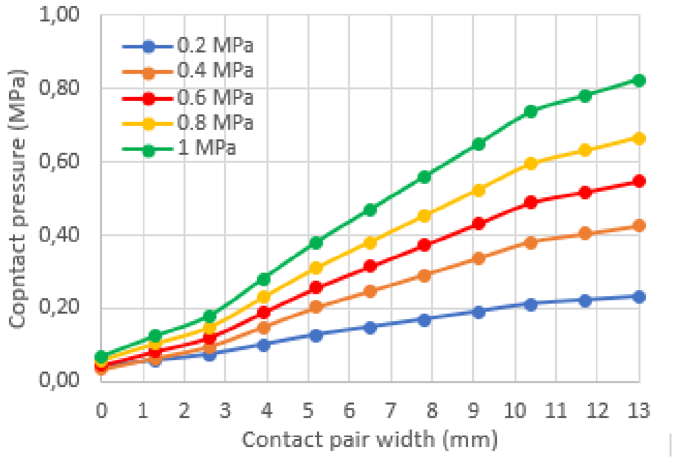
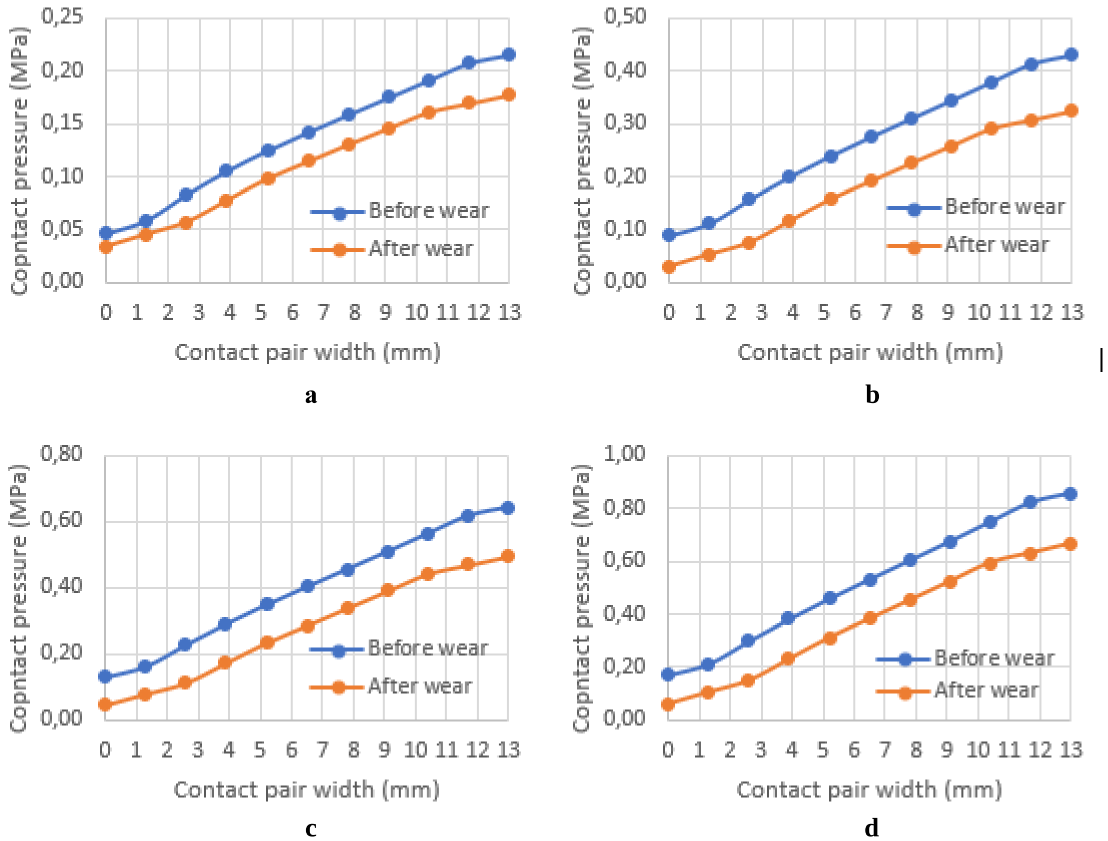
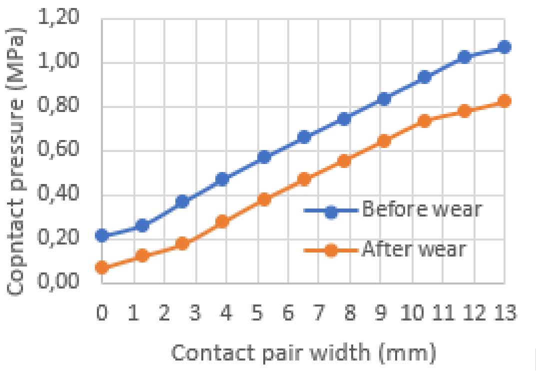


Fig. 8. Contact pressure distribution along the width of the friction pair when the pressure of the working medium changes

In fig. 11 shows the change in the shape of the contact surface. It can be seen from the graphs that the section closer to the exit from the seal experiences the greatest loss of material. That is, as mentioned above, in places of higher values of contact pressure. It is also worth noting the fact that as the shaft rotation linear velocity increases, the amount of material loss increases in direct proportion.

Separately, it should be noted that the obtained modeling results may have a slightly idealized picture of the wear of the contacting surfaces, as the effect of abrasive inclusions that may be present in the medium of the stuffing-box packing seal is not taken into account; misalignment of the shaft and seal and uneven loading of the packing gland, which holds the stuffing box packing inside the chamber, are not taken into account; the degree of washing out of the stuffing box packing impregnation is not taken into account; the effect of temperature is not taken into account. The impact of these factors can be reflected in further study.





e

Fig. 9. Contact pressure distribution before and after wear at applied pressure:
a – 0.2 MPa, b - 0.4 MPa, c – 0.6 MPa, d – 0.8 MPa, e – 1 MPa

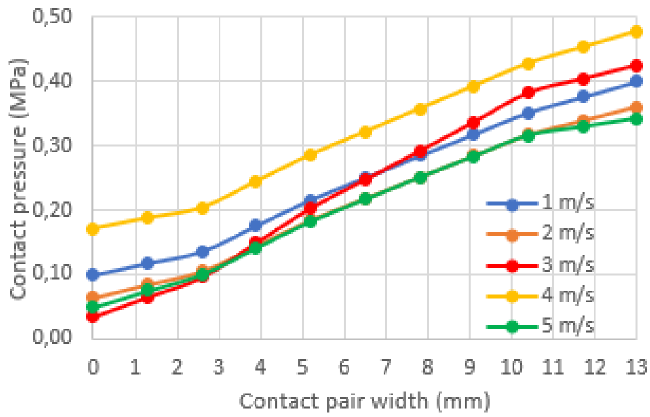


Fig.10. Contact pressure distribution along the width
of the friction pair when the shaft rotation velocity changes

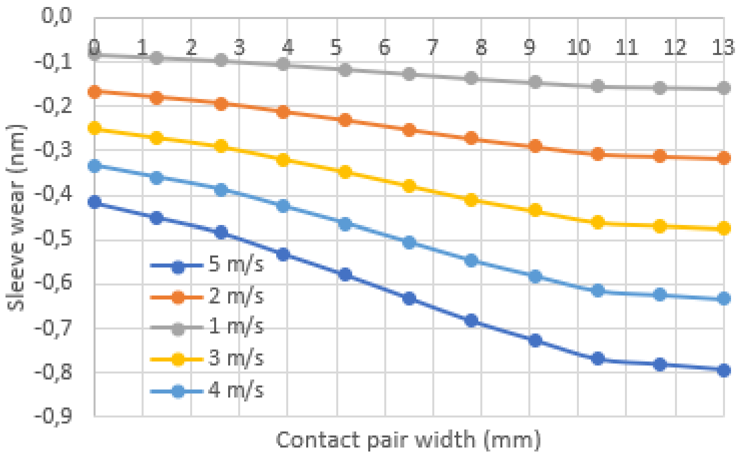


Fig. 11. Changing the shape of the contact surface during time 10^7 s

Nevertheless, despite all the mentioned limitations of the proposed model, it can be used to determine the wear of contacting surfaces. As for stuffing-box packing seals, this model can be used to predict the wear of protective sleeve surfaces and, as a result, specify the time intervals for its service.

Conclusions

The obtained investigation results indicate that the proposed stuffing-box packing seal wear model, built based on the Archard model, sufficiently accurately corresponds to the experimental data at the degree indicators m = 1.5 and n=1.3. Graphic representation of the dependence of the wear volume on the applied load confirms the correspondence of the calculation results to the experimental data with an accuracy of up to 10 %.

The given calculation results indicate that the model considers the influence of applied pressure and shaft rotation speed on the wear intensity. The difference in the influence of these parameters on the wear intensity is explained by the change in the wear degree indicator with the increase in applied pressure.

The obtained results have both theoretical and practical significance. The wear model can be used to predict the wear of the protective sleeve surfaces, which will help clarify the service intervals of the stuffing box packing seals and, therefore, increase their service life. As a result of the solution of the wear-contact problem, the understanding of wear processes in stuffing-box packing seals has been deepened. Addressing the model's shortcomings, such as lack of consideration of abrasive inclusions, no uniform loading, or temperature variation, in further studies may improve its accuracy and applicability.

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Я.І. Сапожников, А.В. Загорулько. Розрахункові дослідження механізму зношення сальникового ущільнення з використанням моделі Арчарда.

Представлено модель зношення сальникового ущільнення, зокрема, поверхні захисної втулки вала. Моделювання виконувалося за допомогою програмного комплексу ANSYS, застосовувався модуль Transient Structural із використанням вбудованої моделі зношення Арчарда. Виконано валідацію моделі зношення у відповідності до результатів попередніх експериментальних досліджень з урахуванням дії робочого тиску. Вперше визначено, що при показниках ступеня в рівняннях Арчарда m=1.5 та n=1.3 запропонована модель зношення дозволяє отримати достатньо точні значення інтенсивності зносу. Порівняно величини відносного зношення для різних матеріалів захисних втулок. Наведено графіки розподілу контактного тиску по ширині пари тертя при різних значеннях робочого тиску та лінійних швидкостей обертання вала. Отримано результати змінення форми поверхні втулки, обумовленої втратою матеріалу. Отримане змінення форми вважається ідеалізованим, так як в цьому дослідженні не враховуються наявність абразивних включень в робочому середовищі, нерівномірний розподіл тиску на натискній втулці, змінення температури та ін. Проте, це дослідження може бути корисним при прогнозуванні зношення основних компонентів сальникового ущільнення.

Ключові слова: зношування, модель Арчарда, сальникове ущільнення, розподіл контактного тиску, об’ємна втрата матеріалу

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Resource testing of modified plain bearings for the aviation industry

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Abstract

The resource tests of plain bearings with metal-polymer tribo-systems developed for the aviation industry are presented. The purpose of the work is to determine the wear resistance of modern anti-friction polymer materials in plain bearings in comparison with metal fluoroplastic tape. The uniqueness of the tests lies in the use of a combination of high-performance polymer materials in a pair with chromium and molybdenum coating during the reversible movements of plain bearings. Since the use of such bearings is mass in nature, the use of titanium materials in the manufacture of bearing cages will allow to significantly reduce the weight of the aircraft and increase its efficiency. It was determined that a plain bearing with a polymer material of carbon and polyamide fibers and PTFE with functional additives shows a wear resistance 1.8-2 times greater on the segment of 40-100 thousand cycles than bearings with other materials during laboratory resource tests. Also, industrial tests have established that after 2 million cycles, a hinged bearing with a metal-polymer tape shows a result that is 1.2-1.5 times lower in wear resistance than polymer materials, but all these results are within the tolerances of normal bearing operation. Industrial tests have proven that at replacing the inner ring of a plain sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. Technological recommendations have been developed and a new design and materials of plain sliding bearings with polymer anti-friction coatings for the aviation industry have been proposed. The implementation of technological recommendations in the production of bearings will allow to move away from the universality of the use of plain bearings and extend their wear resistance and durability in general due to the use of the full thickness of the polymer material and the development of bearings with predicted characteristics for a specific task.

Keywords: plain bearings, metal-polymer tribo-systems, durability, wear resistance, reversible movement, loading, coating, titanium alloy, polymer antifriction materials.

Introduction

Plain sliding bearings are widely used in machine building and the aviation industry. They are used for: work in aggressive environments, with high vibration and shock loads, in fixed joints and everywhere where high contact loads and low sliding speeds are required. They are designed to transmit radial, axial and combined loads in moving or stationary connections of machines and mechanisms. They are used to compensate for distortions, temperature and elastic deformations that occur during the operation of aircraft. A special place in the line of plain bearings is occupied by bearings with materials that do not require lubrication during the entire service life of the bearing.

Bearings with metal-polymer tribo-systems are quite widely used in friction units. Different combinations of metal and polymer structural elements make it possible to predict friction nodes for a specific task. In turn, polymeric materials in most cases are quite complex after their modification with functional, as a rule, antifriction fillers.

Literature review

Metal-polymer tribo-systems and polymer composite materials play a progressive role in tribotechnics. They are used to replace scarce metals and alloys, significantly increase the manufacturability, reliability and durability of friction units. Units of machines using polymer composite materials have a smaller mass, work almost silently, have high damping capacity, do not require lubrication. This is especially true for the aviation industry. Parts made of polymer materials can be operated in vacuum and chemically active environments, at cryogenic and elevated temperatures, in a wide range of loads and sliding speeds. Currently, anti-friction polymer materials are widely used in transport and power engineering, technological equipment and household appliances, covering a huge range of friction nodes for technical and medical purposes, starting with lining plates of hydroelectric power plants and ending with microrobots for blood purification [1, 2].

The use of polymer composite materials allows significantly reduce the labor cost of manufacturing parts of friction nodes due to high-performance and resource-saving technologies. For example, when replacing metals with cast plastics, labor costs are reduced by 5...6 times, and the cost price by 2...5 times; when using polymer materials instead of metals and semi-finished products based on them, the cost of the product is reduced by 4...9 times [3].

According to the definition, a composite material consists of one or more continuous phases of a homogeneous matrix with one or more dispersed phases. In this regard, the reliable operation of metal-polymer tribo-systems primarily depends on the structural and morphological factor that affects the tribomechanical characteristics of materials [4]. The principle of obtaining composite materials consists of a previously created combination of two different phases (fillers and matrix) using certain technological techniques. As a result of the filling, materials are obtained, the physical and mechanical properties of which differ from the matrix. The choice of fillers for metal-polymer materials depends on the purpose of the material, the need to change certain tribomechanical characteristics and the type of polymer matrix.

Usually, polymer composite materials used in sliding bearings are divided into composite materials reinforced with continuous fibers or fabrics, dispersion-reinforced composite materials, composite materials based on mixtures of polymers that are not capable of dissolving in each other and are characterized by a certain distribution of polymer particles of the same nature in matrices of another polymer.

Plain sliding bearings with metal-polymer tribo-systems are very popular in the aviation industry [5]. They are made of stainless and corrosion-resistant steels and do not require maintenance. They are compact, have an extremely high weight-to-weight ratio and are used in primary and secondary flight control systems. They have a hinged design. The inner ring is made of high-quality steel with a polished spherical surface. The outer ring is equipped with a composite metal-polymer material based on polytetrafluoroethylene with tin-based bronze (metal-polymer tape). In order to precisely fit the spherical surface of the inner ring and ensure an optimal sliding surface, the outer ring is produced by cold forming around the inner ring.

Recently, many high-tech engineering anti-friction polymer materials have appeared on the market for their use in tribo-nodes of machines [6, 7]. According to their characteristics, these materials in some cases exceed the wear resistance p removing the bearing from the installation. Control was carried out according to the ГОСТ 3635-78 (item 4.10) scheme using a time-type indicator. The control was carried out 3 times for the reliability of the values for each point of the graph. The contact fatigue cracking of the bearing surfaces after the total test cycle after 100,000 cycles was also determined.

4. The frequency of oscillations was 3 Hz.

5. The amplitude of the oscillations was 40 degrees (± 20°) and was determined from the conditions of the kinematic diagram of the lever of the helicopter's swashplate.

6. The load for all tested bearings was 31.5 kN. The load scheme corresponded to ГОСТ 3635-78, chapter 6 "Operating conditions".

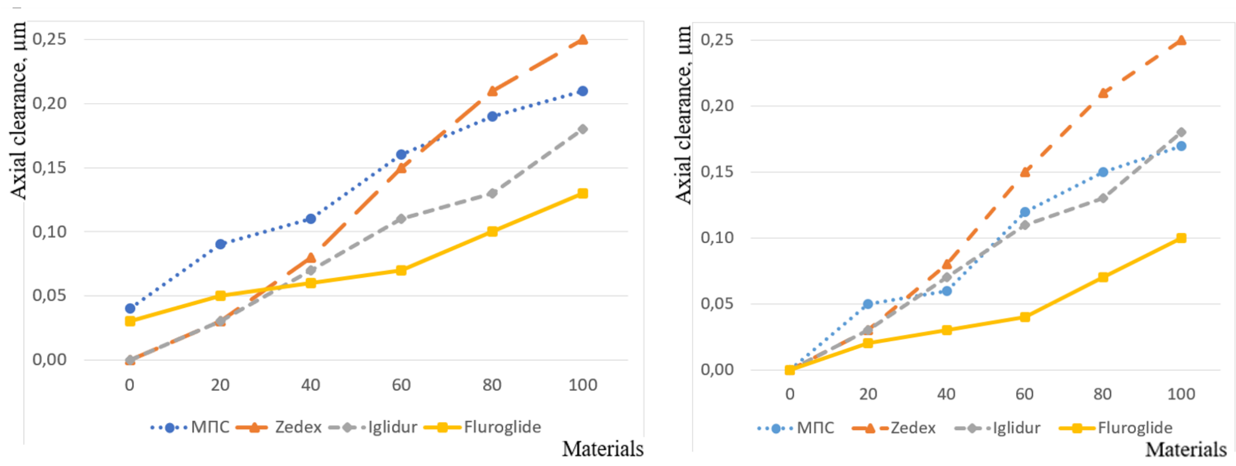
7. All tests were carried out at a temperature of 16 to 20 °C. In the course of research, a slight increase in the temperature of the plain bearings up to 40 °C was observed.

Resource laboratory tests of plain bearings with polymer materials

In the process of testing plain bearings with metal-polymer coatings, the shedding of polymeric materials in the form of black wear products was observed in all tested samples. After testing for 100,000 cycles, the fractographic analysis did not reveal any seizure sites on the surface of the inner clip. The outer clips with metal-polymer materials did not wear down to the base of the bearing, which may indicate that all plain bearings that participated in the tests are functional and can withstand a longer life, according to ГОСТ 3635-78, DIN ISO 12240-1 (DIN 648) та СТП 651.02.061-92. It should also be noted that all pivot bearings showed an axial gap of less than 0.3 mm after 100,000 cycles, which is considered a critical gap for a bearing of this size.

The results of resource tests are presented in fig. 1. According to ЕТУ 100-4, ГОСТ 3635-78 та DIN ISO 12240-1 (DIN 648), articulated bearings of this type and size should be manufactured with a gap of 0.03-0.08 mm, which corresponds to (Fig. 1, and) during initial measurements of ШН30ЮТ та GE30EW-2RS bearings. However, when bearings were made with other polymer materials, the clearance of the new articulated bearings was zero. What is associated with the peculiarity of the production of trial samples of bearings with ZX-324VMT and TX1 materials.

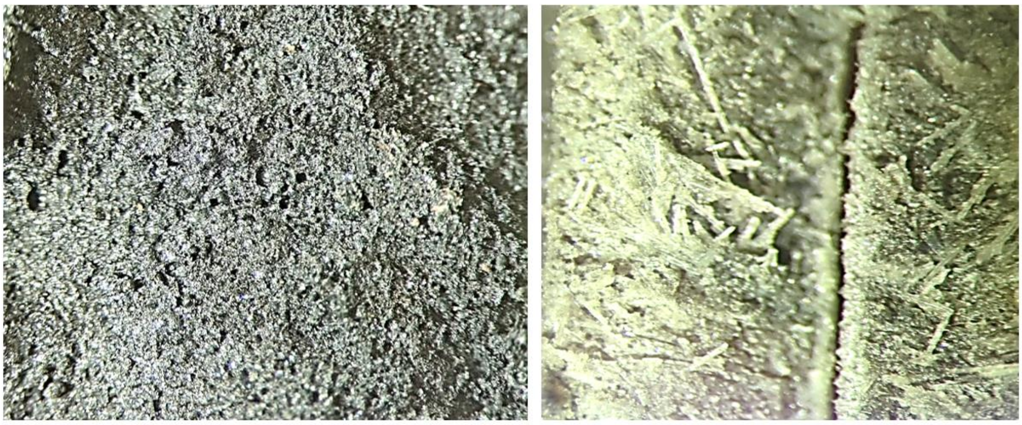
Analyzing the test results of plain sliding bearings, it can be concluded that the bearing with metal-polymer tape and the bearing with Fluroglide material have almost equidistant curves, which are similar in the nature of wear. The difference is observed only in the axial gap results. Initially, the spherical bearings have a certain clearance and the polymer material (PTFE with functional additives) is in a free, uncompressed state. When the load is applied, the compression of the PTFE material, which is part of these polymers, and the so-called running-in of the bearings are observed. Which is characterized by the distribution of the material and the filling of all pores under load and the establishment of a certain wear pattern. This is exactly what the picture shows us. 1 at the primary stages of testing with a run-in time of 20,000 oscillations. When the number of working hours increases to 100,000, uniform wear of the material occurs almost linearly. It should be noted that during the tests, the temperature of the bearing with Fluroglide material rose to 43°C. The GE30EW-2RS bearing heated up more than the metal polymer tape bearing. This is explained by the removal of heat from the friction zone of the face into the inner ring and the metal-polymer contact, and in the bearing with a metal-polymer tape, the contact is metal-(babbit + polymer).



a b

Fig. 1. Dependence of the axial gap (wear) of plain bearings with metal-polymer materials on the number of oscillation cycles at actual values (a) and under the condition of equalization of the initial axial gap (b).

Analyzing the wear resistance of plain bearings with ZX-324VMT and TX1 materials, it can be said that up to 20,000 oscillations, the wear resistance of these materials is the same. It is explained by the fact that the surfaces of the polymer materials of the Zedex and Iglidur companies are almost identical in terms of characteristics. As the number of operations increases and as the surface layers of polymer materials wear, the structure and functional additives that are part of the polymer materials become more and more apparent. In fig. 2 shows the topography of ZX-324VMT and TX1 material structures. It can be seen from the figure that the Iglidur company uses a larger size of reinforcing fibers for strengthening. At 100,000 cycles, it can be seen that the wear resistance of the ZX-324VMT material is the lowest. The difference is already evident after 70,000 cycles. The TX1 material during the tests occupies an intermediate position between the metal-polymer tape and the Fluroglide material.



a б

Fig. 2. Structures of polymer materials ZX-324VMT (a) and TX1 (b) at magnification of x56.

In general, we can say that up to 60,000 cycles, the plain bearing with a metal-polymer tape shows worse wear resistance than polymer materials, but all these results are within the tolerances of normal bearing operation. If we discard the gap that was at the beginning of the bearing tests and compare the results, the picture of the wear of the plain bearings will be somewhat different. (Fig. 1, b) shows the results of (axial gap) wear of plain bearings with metal-polymer materials from the number of oscillation cycles under the condition of leveling the initial gap (the wear curves of Zedex and Iglidur materials are symmetrically shifted to the zero mark).

Analyzing this version of the wearing of metal-polymer materials, it can be stated that the plain bearing with Fluroglide material shows wear resistance almost 2 times higher in the segment of 40-100 thousand cycles than bearings with other materials. It should be noted that this is the only plain bearing where the wear of the polymer material occurs on the steel, and on the chrome coating, which is known for its wear resistance [10, 11]. The combination of reinforced fabric with PTFE and additives from solid lubricants paired with polished chrome, once again proves that the most successful option for tribo-pairs is a solid base with a viscous matrix and solid inclusions.

It should be noted that the testing conditions of the plain bearings did not correspond to the real operating conditions of the plain bearings, which work, for example, in the levers of swashplate of the main gearbox of a helicopter. And the test results were only comparative at a certain calculated load. The temperature of the tests, the number of cycles and the load were selected according to the normative documents of the operating conditions of the helicopter. For example, the number of hours of operation of the main gearbox and the swashplate as a whole from repair to repair is from 2000 to 2500 hours of operation, depending on the type of equipment and operating conditions of the helicopter. At the nominal rotation frequency of the main rotor of 192±2 rpm, the oscillation frequency of the plain bearing is about 3 Hz, and in terms of cycles, 27 million oscillations at 2500 hours. Turn in low gas mode 45±10 rpm. That is, the value of 100 thousand cycles as well as the load of 31.5 kN are standardized passport values.

Therefore, for more reliable results, it is necessary to conduct additional industrial tests in conditions close to real nodes.

Industrial testing of plain bearings

Industrial tests of plain sliding bearings with metal-polymer materials were carried out at an aircraft repair enterprise, which is engaged in maintenance, overhaul and production of parts and assemblies for helicopters of Mi-8/17 series.

The purpose of the research was to manufacture and test the wear resistance of prototypes of plain bearings that were manufactured at the enterprise on the recommendation of the authors of the work in accordance with the contract. The bearings were manufactured according to the scheme described above, but in addition, molybdenum coating was applied to the inner surface of the plain bearings by the vacuum-arc method with a thickness of about 100 microns. Also, the inner cage of some bearings was made of titanium alloy R56260 (Ti6Al2Sn4Zr6Mo).

The installation on which plain bearings were tested was made according to the scheme presented in [12]. The test bench works on the principle of movement of the outer ring with a given amplitude with a fixed inner ring under a combined radial and axial load. The stand allows tests of both spherical and cylindrical sliding and rolling bearings in the mode of reversible motion in a wide range of angles, frequencies and loads in air as well as in other gases or vacuum. The stand also carried out tests at temperatures with the help of heating with infrared radiation at the place of installation of the hinged bearing.

The choice of material combinations of plain bearings for industrial tests was determined from the standpoint of economic efficiency and reliable working conditions from the introduction of experimental samples into industry. The ШН30ЮТ type bearing was used as the basis, which is currently standardized according to all relevant technical documents. The test results of test samples of plain bearings are presented in Table 1.

For testing of plain bearings, the operating conditions were selected based on the operating modes of the lever of the helicopter's swashplate:

1. The frequency of oscillations is 3 Hz.
2. The testing temperature is 50-55 °C.
3. The load on the bearing was 3 kN in the radial direction.
4. The amplitude of oscillations was ±15°.
5. Research base $2 \cdot 10^6$ cycles.
6. Control of the axial gap at $1 \cdot 10^6$ and $2 \cdot 10^6$ cycles.
7. The sliding speed was 32.7 mm/s.

It should be noted that standard bearings of the type ШН30ЮТ and GE30EW-2RS according to [13] DIN ISO 12240-1 (DIN 648) are manufactured with a clearance of 30-80 μm, and test samples of plain bearings were manufactured with a minimum clearance of 5 μm. It is also noted that the surfaces of all polymer coatings were in satisfactory condition after the tests. There were no damages or tears on the surfaces. The gaps of all samples after the tests were within the tolerance of 0.3 mm.

Analyzing the test results of test samples of plain bearings, it can be said that all samples are within tolerance even after 2 million cycles. Also, for a clearer picture, it is necessary to list the characteristics of the wear resistance of plain bearings and to present the test results in the form that the initial value of the axial gap is excluded. Fig. 3 presents a histogram of the results of the axial gaps of plain bearings without taking into account the initial gap.

Table 1

The results of axial gaps of plain bearings during industrial tests

Sample No.	Polymer on the outer ring	Coating on the inner clip	Inner clip material	Axial gap at the number of working cycles, μm		
				0	$1\cdot10^6$	$2\cdot10^6$
1	Metal-polymer tape	-	95Х18Ш	45	170	200
2	Fluroglide	chrome	95Х18Ш	50	145	155
3	Zedex	-	95Х18Ш	5	120	140
4	Zedex	molybdenum	95Х18Ш	5	120	135
5	Zedex	molybdenum	R56260	5	125	140
6	Iglidur	-	95Х18Ш	5	100	120
7	Iglidur	molybdenum	95Х18Ш	5	95	120
8	Iglidur	molybdenum	R56260	5	105	125

It can be seen from the histogram (Fig. 4) that under moderate loads, in test conditions close to real ones, the selected polymer materials showed better wear resistance results than the metal-polymer tape. This indicates that modern highly modified engineering plastics have better wear resistance (under certain operating conditions) than metal-polymer tape. The FLURO bearing shows the best results in terms of wear resistance. This is confirmed by the experiments of laboratory installations and resource laboratory tests. When analyzing the table. 1, it can be seen that at the beginning of the operation of the bearing, the polymer material is pressed, and the PTFE polymer material is installed in the reinforced fabric. In the future, equilibrium occurs in the zone and all processes of friction and wear of the materials involved in the work are stabilized.

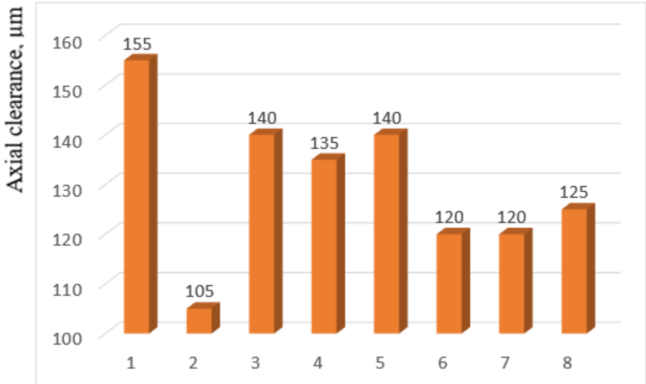


Fig. 3. The results of the axial gap (μm) of the samples without taking into account the initial gap after 2 million oscillation cycles (sample numbers according to Ta

The histogram shows very clearly the groups of samples 3, 4, 5 and 6, 7, 8. When analyzing the wear resistance of bearings with Zedex material, the dependence is followed that with an increase in temperature and a decrease in load, the wear resistance of the material is greater than in laboratory resource tests (Fig. 1). Under operating conditions close to real ones, the wear resistance of the ZX-324VMT polymer exceeds metal-polymer tape by 10-15%. Also, applying a molybdenum coating of 0.1 μm increases the wear resistance of the bearing. The wear resistance of the molybdenum coating on the titanium alloy shows the same results as when the polymer slides on the 95Х18Ш steel. An approximately the same pattern is observed in the TX1 material, but its wear resistance is even greater under these operating conditions. An interesting fact is that when replacing the inner ring of a hinged sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. A slight deterioration in wear resistance can be explained by the fact that the titanium alloy removes heat from the friction zone worse [14, 15] and the temperature in the contact zone is higher, and as a result, the wear of polymers is greater. But despite this, at light or moderate loads, replacing the inner ring of the pivot bearing from steel to a titanium alloy with protective wear-resistant coatings is an excellent option for the aviation industry. Due to the fact that the use of plain bearings is widespread in aircraft, the benefit in weight will be very noticeable. Provided that the polymer material does not wear out to a critical value and the wear-resistant coating on the inner ring will also work for the entire period of operation of the plain bearing, it is possible to manufacture outer rings from titanium materials. The problem is that the use of polymer materials in plain bearings has limited operating conditions than metals or roller bearings.

Conclusions

1. The results of laboratory resource testing of plain bearings with metal-polymer materials are presented. It was determined that the plain bearing with Fluroglide material shows a wear resistance of 1.8-2 times greater

on the segment of 40-100 thousand cycles than bearings with other materials. It was also established that, up to 60,000 cycles, a plain bearing with a metal-polymer tape shows worse wear resistance than polymer materials, but all these results are within the tolerances of normal bearings operation.

2. Industrial tests have proven that at replacing the inner ring of a plain sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. At low or moderate loads, replacing the inner ring of the plain bearing made from steel to a titanium alloy with protective wear-resistant coatings gives a significant gain in the aircraft weighting.

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Хімко М.С., Хімко А.М., Мнацаканов Р.Г., Мікосянчик О.О. Ресурсні випробування модифікованих шарнірних підшипників для авіаційної галузі

Представлено ресурсні випробування шарнірних підшипників із металополімерними трибосистемами розроблені для авіаційної промисловості. Метою роботи є визначення зносостійкості сучасних антифрикційних полімерних матеріалів у шарнірних підшипниках в порівнянні їх із металофторопластовою стрічкою.

Унікальність випробувань полягає у використанні комбінування високоефективних полімерних матеріалів в парі із покриттям хрому та молібдену при реверсивних рухах шарнірних підшипників. Оскільки застосування подібних підшипників носить масовий характер, застосування титанових матеріалів у виготовленні обойм підшипників дозволить суттєво зменшити вагу повітряного судна та підвищити його ефективність.

Визначено, що шарнірний підшипник з полімерним матеріалом із вуглецевих і поліамідних волокон та PTFE із функціональними добавками показує зносостійкість в 1,8 - 2 рази більшу на відрізку 40-100 тис. циклів, ніж підшипники із іншими матеріалами при лабораторних ресурсних випробуваннях. Також промисловими випробуваннями встановлено, що при наробітку в 2 млн. циклів шарнірний підшипник із металополімерною стрічкою показує результаті в 1,2-1,5 разів нижче по зносостійкості ніж полімерні матеріали, але всі ці результати лежать в полі допусків нормальної роботи підшипників.

Промисловими випробуваннями доведено, що при заміні внутрішнього кільця шарнірного підшипника ковзання на титановий сплав із покриттям молібдену зносостійкість майже однакова або незначно нижче чим при терті полімеру по сталі. Розроблені технологічні рекомендації та запропоновано нова конструкція та матеріали шарнірних підшипників ковзання із полімерними антифрикційними покриттями для авіаційної промисловості. Впровадження технологічних рекомендацій у виробництво підшипників дозволить відійти від універсальності використання шарнірних підшипників та продовжити їх зносостійкість та довговічність в цілому за рахунок використання повної товщини полімерного матеріалу та розробці підшипників із прогнозованими характеристиками під конкретну задачу.

Ключові слова: Шарнірні підшипники, металополімерні трибосистеми, довговічність, зносостійкість, реверсивний рух, навантаження, покриття, титановий сплав, полімерні антифрикційні матеріали

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Methodology and results of the study of physical, mechanical and tribological characteristics of nitrided inner surfaces of long holes

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Abstract

Created control device physico-chemical and tribological characteristics of nitrided internal surfaces of long holes, which is a hollow pipe with radial holes made at a certain distance from its ends to ensure the ratio of the height of the center of the sample to the internal diameter of the pipe from 0 to 10 or more, which differs in that the height of the samples simulates the depth of the longitudinal holes, and the samples themselves to facilitate their fixation and to ensure the absence of electric spark discharge near the ends, they are installed with a certain tension. At the same time, the length of the cylindrical sample is equal to the thickness of the pipe wall.Thus, each sample is nitrided from two ends, which makes it possible to nitride from the outside and from the middle of the model at almost the same temperature, as well as to compare the results of nitriding of two surfaces (external and internal). At the same time, the difference in conditions is only in the location of these surfaces - external or internal. All other factors that could affect the results of the modification are practically identical. However, nitriding in a glow discharge with a constant current supply does not ensure the treatment of the inner surface uniformly throughout the entire depth, and with significant ratios of length to diameter (more than 4), the inner surface of the hole remote from the ends is practically not nitrided. Therefore, a process technology and a device for quality control of anhydrous nitriding in glow discharge (BATR) of long holes with cyclically switched power supply of the gas discharge chamber have been developed.

Keywords: long holes, cyclically switched discharge, wear resistance, dry friction

Introduction

Practically all kinematic pairs of friction with translational movement structurally fall under the category of holes with a relatively small diameter, that is, the ratio of the length (depth) of the hole to its diametrical size exceeds the value of four [1]. This indicator, accepted as a criterion of geometric ratios, is justified by the fact that the nitriding process of similar structural elements is similar in nature to a discharge with a hollow cathode [2]. From the theory of this process, it is known that the real field penetrates inside the holes to a depth of no more than two diameter sizes (if the holes are not round, then two smaller diameter sizes). The numerical criterion for assigning nitriding objects to the category of holes with a relatively small diameter in the number of four diameters applies to structures in which the holes are through. For blind recesses or holes, the value of the criterion can be reduced to two.

Holes of a relatively small diameter in details should be considered through or blind holes, the ratio of the length of which to the diameter is greater than 2 - 4. The justification for these limits (a smaller value is for non-through holes) is that, as established in [1], the depth of the hole is two diameters, the intensity of the electric discharge field is only 0.02% of the intensity at the end of the hole. Taking into account this indicator, through holes whose length to diameter ratio is greater than three can be considered relatively small diameter holes, and for non-through holes - 1.5.

Literature review

Currently, in surface engineering methods, preference is given to the implementation of methods of controlled modification of surfaces based on the action of concentrated energy flows. Vacuum, ion and laser technologies, which are promising from the point of view of forming the structure and properties, have gained the greatest development. These methods of surface modification went through several stages, which led to the creation of a large number of technical solutions determined by both the specifics of the processes and the design features of the equipment used. One of the most developed and widely used in world practice is the method of anhydrous nitriding in a glow discharge. The paper [3] investigates the possibility of creating modified surface layers on austenitic stainless steels using low-pressure glow discharge nitrogen treatment, similar to sputtering, so that surface activation, heating, and nitrogen incorporation can occur in one step with a short duration. In work [4], it was established that with the help of appropriate treatment parameters, glow discharge nitriding can significantly improve the corrosion resistance of austenitic stainless steels, such as AISI 316L and AISI 202, compared to untreated alloys. In work [5], stationary helicon wave plasma with a small diameter (10 mm) was used for nitriding the inner part of a thin austenitic stainless steel tube. The results confirmed that the nitrided layer consists mainly of the austenite phase, iron nitride is not released. Given the successful control of the plasma discharge in a thin tube with a small diameter, this research paves the way for achieving high-performance nitride layers inside thin tubes. In work [6], the process of low-temperature plasma nitriding was proposed as a surface treatment to increase the technical durability of stainless steel tubes and nozzles. Various analyzes were performed to describe only the internal process of nitriding, from the inner surface of the pipes and nozzles to their depth in the thickness. The authors in the study [7] developed technological methods of pulsed ion-plasma nitriding of internal cylindrical surfaces using a hollow perforated anode. This leads to the formation of diffusion coatings consisting of areas of different chemical and phase composition. The purpose of the work [8] was to evaluate the possibility of nitriding deep holes of small diameter. The tests were carried out on cylindrical samples of unalloyed and low-alloyed steel with electro-drilled and mechanically hollow through and blind holes.

Attempts to nitride long holes in a glow discharge with constant power supply only confirm the above theoretical conclusions regarding the spread of the discharge in holes of relatively small diameter. At the same time, the inner surfaces of the holes near the ends are nitrided with acceptable quality, while when the distance from the end of the hole increases, the results of nitriding become less and less noticeable. Some improvement in the effects of the modification can be achieved by increasing the duration of the process. That is, the effect of ordinary furnace nitriding is manifested, but at the same time, the main advantage of nitriding in the glow discharge is eliminated - a significant reduction (by more than an order of magnitude) in the duration of processing [2] .

Thus, the task set in the work has, first of all, practical significance, since there are many options for its real production application. At the same time, one should take into account the fact that such a process has not been sufficiently studied, except for purely technological aspects [9]. A preliminary theoretical justification for the possibility of nitriding the inner surfaces of holes of a relatively small diameter can be the thesis of pumping nitrogen ions into the inner cavity of the hole due to the effect of their movement by inertia at the moment of changing the discharge voltage up to its complete disappearance during a cyclically switched discharge. Since, in the absence of an electric field, the ions will continue to move tangentially to the trajectory that took place at the moment of termination of the discharge, it becomes possible for them to reach the region of the hole cavity, where the field is practically no longer active. This phenomenon is especially characteristic of ions that fly into the hole in the vicinity of its center. At the same time, the trajectory of their movement is significantly straightened, the probability of collision of ions with the walls of the hole decreases, they fly a much longer path than it would be in the case of continuous power [10]. In this way, an excess concentration of nitrogen ions is created, which further drift into the depth of the hole, obeying the laws of diffusion. Since nitrogen ions are the main factor in the formation of nitrides, the nitriding process of the inner surface should theoretically occur at a speed that practically corresponds to the conditions of processing open surfaces [11]. The influence of the physical foundations of the nitriding process on the contact interaction of modified friction surfaces is considered in [12]. The conducted analysis confirmed the determining importance of the structure and composition of the gas discharge environment.

Known works on the use of pulse discharge in nitriding processes in order to improve the mechanical and tribological properties of surface layers. In work [13], with the aim of optimizing the nitriding process, experimental studies of pulsed plasma nitriding of carbon steel DIN C45 (AISI C1043) were carried out using a direct current pulse glow discharge. The influence of gas composition, temperature, processing time and frequency on layer thickness and microhardness was studied. The obtained results are recommended for the optimization of the nitriding process and computer control of the process. In order to increase the tribological and properties of austenitic stainless steels in [14], the authors use plasma nitriding of the surface in pulse mode. It has been found that the wear rate is reduced by up to 90% compared to the base material when processed with a low duty cycle. It is shown that wear resistance and corrosion resistance can be significantly increased by reducing the pulse duty cycle. In work [15], samples of unalloyed steels were nitrided under fixed conditions using an alternating pulse current. It was established that the hardness and wear resistance increase significantly with an increase in the pulsed current. This study comprehensively explains the contribution of pulsed current to nitriding efficiency and plasma reactivity. In the study [16], a pulsed power supply is used for plasma nitriding to overcome the problems of direct current plasma nitriding. Therefore, the use of a pulsed power supply ensured: more accurate control of the nitriding process, post adjustment of the pulse width, avoidance of the phenomenon of arcing on the surface of the workpiece. Therefore, the advantages of using a pulsed discharge as a power source during nitriding are obvious, but its use for processing long holes has not been widely used.

The practical importance of solving the given problem is extremely great, since in mechanical engineering in almost all industries, many parts with holes of relatively small diameter are used, the inner surface of which is working and whose wear resistance is of fundamental importance for increasing the resource of products, their efficiency and the term of normal operation. Examples of such parts can be the inner surfaces of pneumatic and hydraulic cylinders, the inner surfaces of material cylinders of injection molding machines, the inner surfaces of plunger pumps of engine fuel equipment, etc.

Various technologies for modifying the internal surfaces of similar pairs are used: furnace nitriding, cementation, gas chrome plating, etc. But all of them have a number of important disadvantages: the fragility of the surface layers, the long duration of the saturation process during furnace nitriding (96 hours), the change in dimensions and the need for further finishing during cementation.

All the mentioned disadvantages are absent when using the technological process of nitriding in an anhydrous glow discharge. The part before the modification is processed in the finished dimensions, which significantly affects the cost of manufacturing parts. The process is an order of magnitude less long compared to the furnace process, and when using nitriding in anhydrous environments, it becomes possible not only to meet all the requirements of environmental safety, but also to significantly reduce the fragility indicators.

However, nitriding in a glow discharge with a constant current supply does not ensure the treatment of the inner surface uniformly over the entire depth, and with significant ratios of length to diameter, the inner surface of the hole remote from the ends is practically not nitrided. Therefore, the technology of the process of anhydrous nitriding in a glow discharge with cyclically switched power supply of the gas discharge chamber was developed.

Research methodology

To check the nitriding quality of the internal surfaces of long holes (to control the physico-mechanical and tribological characteristics of the nitriding layers), a device was created, which is a hollow cylinder in which series of radial holes are drilled at different distances from the end. Samples made of different steels are inserted into these holes. Thus, each sample is nitrided from two ends, which makes it possible to nitride from the outside and from the middle of the model at almost the same temperature, as well as to compare the results of nitriding of two surfaces (external and internal). At the same time, the difference in conditions is only in the location of these surfaces - external or internal. All other factors that could affect the results of the modification are practically identical (Fig. 1).

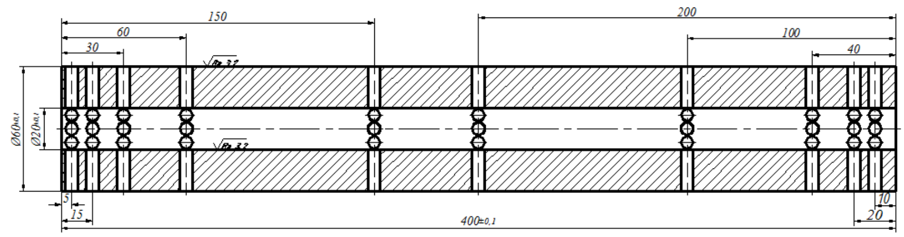


Fig. 1. Hollow cylinder for simulating nitriding of long holes

The presence of a series of radial holes creates the possibility of simultaneous nitriding of samples made of different steels at the same parameters of the technological process, which significantly speeds up experimental research. Full length model400 mm, hole diameter40 mm. Thus, the largest coefficient of the ratio of the length of the hole to its diameter was 10.

Nitridingwas carried out at the unit for anhydrous nitriding UATR-1. A nitrogen-argon mixture was used as a gas medium with a ratio of components by volume of 75% nitrogen and 25% argon. Samples made of steel 38X2MUA were installed in radial holes and held there due to a certain tension (Fig. 2). This achieved not only retention of the samples in the holes, but also the absence of burning near the ends of the samples, especially when fed with a direct current discharge. The appearance of this phenomenon is quite real, as it is observed even with gaps of the order of 0.5 mm. At the same time, the use of a similar method of fixing samples significantly simplifies the design of the model, eliminating from it devices such as screw clamps, collets, etc.

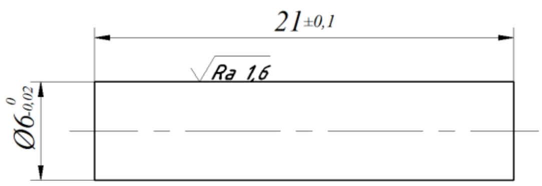


Fig. 2. Sample sketch

The parameters of the technological mode are presented in Table 1. In mode 1, cyclically switched discharge was used, and in mode 2, constant power supply of the gas discharge chamber was used.

Table 1

Technological parameters of nitriding

Mode number	Temperature,°C	Voltage, V	Pressure in the cell, Pa	Duration, hours	Features regime
1	560	730	160	6	The model is open from two sides
2	560	730	160	6	The model is open from two sides

The processing of nitriding results primarily involved measuring the surface microhardness on a PMT-3 microhardness tester. At the same time, the surface microhardness was studied not only on the ends of the samples, but also along the depth of the modified layer. Microhardness measurements were performed at a distance from the surface of 25, 50, 75, 100, 150, 200, 250, 300, 600, 1000 μm.

X-ray phase analysis of nitrided samples was performed on a DRON-3 diffractometer in filtered radiation of an iron anode in the range of q angles from 20° to 100° with a scan step of 0.1° and an exposure time of 10 s. X-ray imaging was carried out from the surface to the depth of the nitrided layer.

Experimental studies of samples for wear resistance were carried out on a universal machine for testing materials for friction, model 2168UMT. The material of the counterbody is steel SHX15 with a base hardness of HRC61; pressure in the contact zone P = 16 MPa; sliding speed v = 0.1 m/s; the controlled parameter is linear wear h, which was determined as a change in the linear size of the sample measured normal to the friction surface as a result of passing a section of length l. The tests were carried out in the modes of extreme [8] and dry [9] friction, which is typical for many parts of mechanical engineering and agricultural machinery.

Research results

Table 2 shows the distribution of the surface microhardness of the internal end surfaces of samples made of 38X2MUA steel depending on the distance of their location from the ends of the model (pipes).

Table 1

Distribution of surface microhardness along the depth of the model

Mode No	Material	The microhardness of the surface is HV0.1 at the depth of the model								
		10 mm	20 mm	40 mm	100 mm	200 mm	250 mm	340 mm	370 mm	395 mm
1	38X2MUA	1098	1096	1097	1098	1097	1096	1098	1097	1098
2	38X2MUA	1100	1096	1090	1019	960	996	1050	1092	1090

For greater visibility, the data in the table. 2 are illustrated in fig. 3.

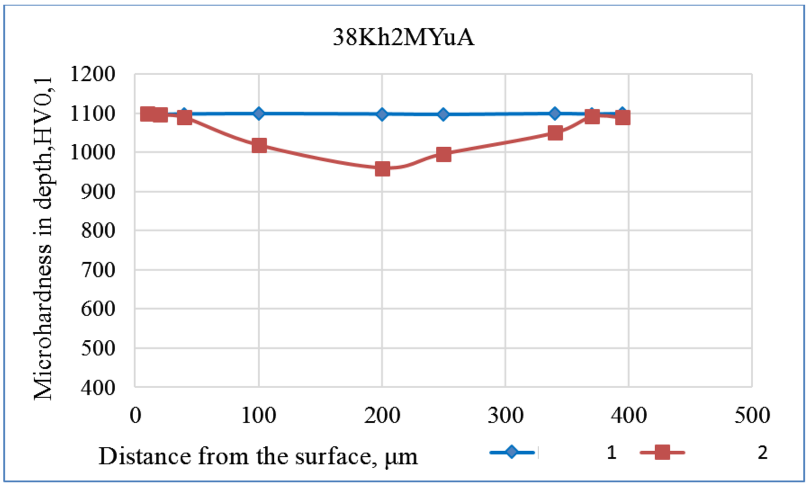
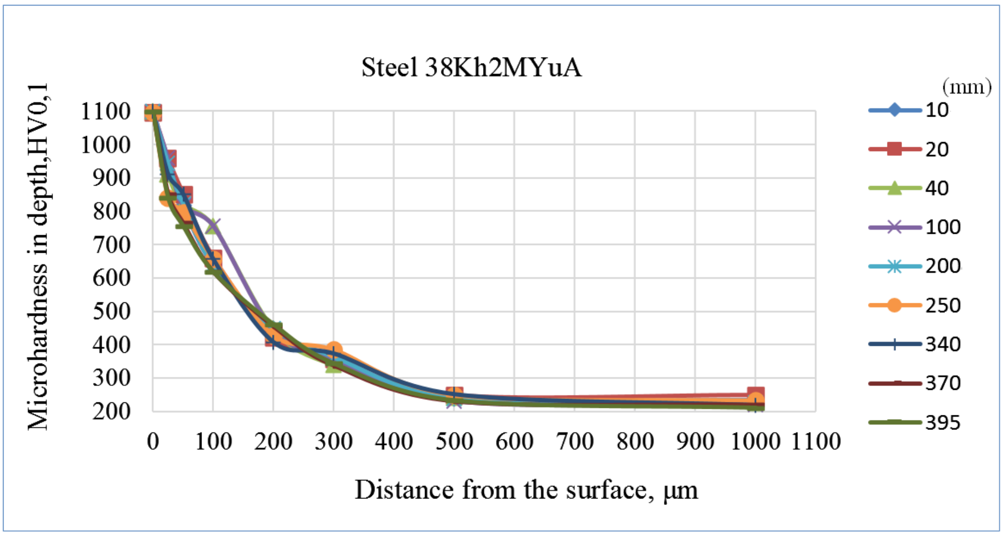


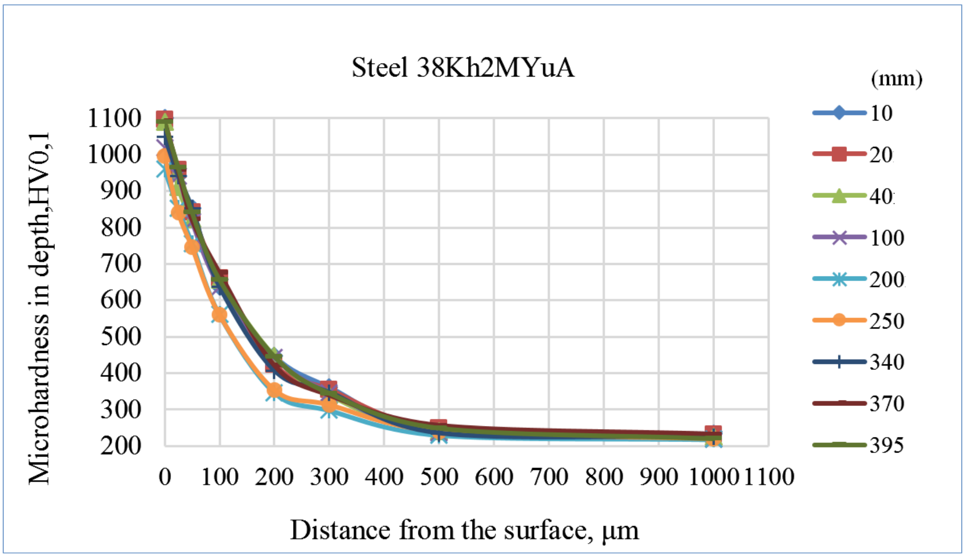
Fig. 3. Dependencies of surface microhardnesssteel 38X2MUA, nitrided in a glow discharge with cyclically switched and constant power supply for the inner surface of the sample

As can be seen from fig. 3, surface microhardness during nitriding in TSR (mode 1).along the height of the pipe, the modified layer of 38X2MUA steel, respectively, from the side of the inner ends remains constant, and during nitriding with direct current, it decreases and reaches a minimum for samples placed in the center of the pipe (mode 2).

A similar conclusion can be drawn from the analysis of the distribution of microhardness along the depth of the nitrided layer strengthened by nitriding in the glow discharge depending on the power supply mode of the gas discharge chamber (Fig. 4, a, b). During nitriding in a cyclically switched discharge, the distribution of microhardness over the thickness of the hardened layer is more uniform and practically the same for all samples along the entire length of the model. In addition, the value of microhardness in the thickness of the nitriding layer is higher during nitriding in a cyclically switched discharge than during constant power supply. Thus, for the sample placed in the center of the model (l = 200mm), the microhardness at the depth of the nitrided layer of 25, 50, and 100 μm was 852, 756, and 561 Pa, respectively, with constant feeding and 942, 822, and 638 Pa with nitriding in a cyclically switched discharge .



a

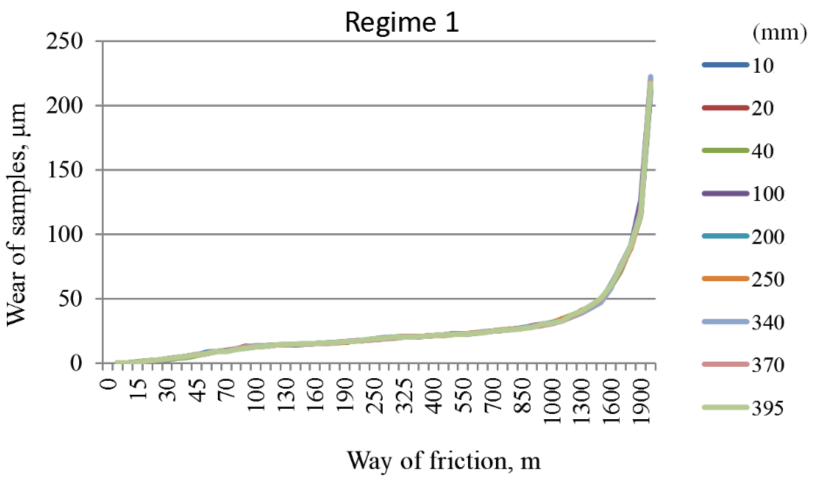


b

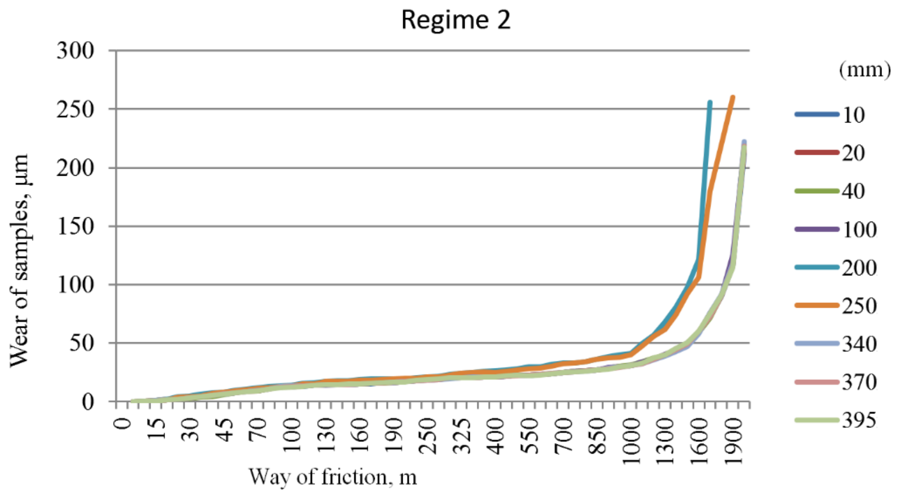
Fig. 4. Distribution of microhardnessfor nitrided steel 38X2MIOA: a – cyclically switched power supply; b - constant power supply

The study of the microhardness of the nitrided layers, its distribution along the depth of the nitrided layer (Figs. 3, 4) indicates the formation of highly nitrogenous phases during nitriding in the TSK. The obtained radiographs confirm this conclusion.

The results of tribological tests showed (Fig. 5) that nitriding in the TSR is a fairly effective way of strengthening the inner surfaces of long holes. Comparison of the wear resistance of 38X2MUA steel samples nitrided according to mode 1 and mode 2, depending on the height of their placement in the pipe, shows its significant increase (by 1.3...1.6 times) during nitriding in the TSR.



a



b

Fig. 5. Wear resistance of nitrided steel samples 38X2MIOA during dry friction depending on the friction path and their location from the ends of the pipe: a – TSR, b – direct current

Therefore, the use of the developed device makes it quite easy to assess the physico-mechanical and tribological properties of the internal surfaces of long holes depending on the distance of their placement from the end of the model hole.

Conclusion

Thus createda device for controlling the quality of nitriding of the inner surfaces of long holes, which is a hollow pipe with radial holes made at a certain distance from its ends to ensure the ratio of the height of the placement of the center of the sample to the internal diameter of the pipe from 0 to 10 or more, which is distinguished by the fact that the height of placement samples simulates the depth of long holes, and the samples themselves are installed with a certain tension to facilitate their fixation and ensure the absence of electric spark discharge near the ends. At the same time, the length of the cylindrical sample is equal to the thickness of the pipe wall.

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Стечишин М.С., Диха О.В., Стечишина Н. М., Здоренко Д.В. Методика і результати дослідження фізико-механічних та трибологічних характеристик азотованих внутрішніх поверхонь довгомірних отворів

Створено пристрій для контролю фізико-хімічних та трибологічних характеристик азотованих внутрішніх поверхонь довгомірних отворів, який являє собою пустотілу трубу з радіальними отворами виконаними на певній віддалі від її торців для забезпечення відношення висоти розміщення центру зразка до внутрішнього діаметра труби від 0 до 10 і більше, який відрізняється тим, що висота розміщення зразків моделює глибину довгомірних отворів, а самі зразки для полегшення їх фіксації та забезпечення відсутності електроіскрового розряду біля торців встановлюються з певним натягом. При цьому довжина циліндричного зразка дорівнює товщині стінки труби. Таким чином, кожний зразок азотується з двох торців, що дає можливість азотувати із зовні та з середини моделі при практично однаковій температурі, а також порівнювати результати азотування двох поверхонь (зовнішньої та внутрішньої). При цьому різниця в умовах полягає тільки в розташуванні цих поверхонь – зовнішнє чи внутрішнє. Всі інші фактори, які могли б впливати на результати модифікації практично ідентичні. Проте азотування в тліючому розряді при постійному струмові живлення не забезпечує обробку внутрішньої поверхні рівномірно по всій глибині, а при значних відношеннях довжини до діаметра (більше 4) внутрішня поверхня отвору віддалена від торців практично не азотується. Тому розроблена технологія процесу і пристрій для контролю якості безводневого азотування в тліючому розряді (БАТР) довгомірних отворів з циклічно-комутованим живленням газорозрядної камери.

Ключові слова: довгомірні отвори, циклічно-комутований розряд, зносостійкість, сухе тертя

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Establishing the regularity of wear of a cylindrical brush of the mounted sweeping equipment of a garbage truck depending on its rotation frequency

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Abstract

The article is dedicated to establishing the regularity of wear of a cylindrical brush of the mounted sweeping equipment of a garbage truck depending on its rotation frequency. Using the mathematical dependencies and corresponding regression analysis programs, it was established a power law of change in the wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on the frequency of its rotation, which can be used to build a mathematical model of the hydraulic drive of the improved mounted sweeping equipment of a garbage truck, taking into account the wear of its working bodies. A graphical dependence of the change in the wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on its rotation frequency was plotted, which confirmed the sufficient convergence of the obtained regularity. The graph of the influence of the rotation frequency of the cylindrical brush of the garbage truck's mounted sweeping equipment on its wear demonstrates the expediency of its reduction. It has been established that for a Ukrainian-made sweeping machine of the serial model KO-713-01, which is equipped with a cylindrical brush with a rotation speed of 3200 rpm, its wear according to the obtained regularity will reach 86.5 mm. It was found that reducing the rotational speed of the cylindrical brush of the garbage truck's mounted sweeping equipment from 62 sec^{-1} (3700 rpm) to 26...38 sec^{-1} (1550...2250 rpm) leads to a decrease in its wear by 2 orders of magnitude. The expediency of conducting additional research to identify further ways to improve the wear resistance of the cylindrical brush of the garbage truck's mounted sweeping equipment has been established.

Key words: wear, rotation frequency, mounted sweeping equipment, cylindrical brush, garbage truck, regularity, regression analysis.

Introduction

Increasing the wear resistance, durability, and reliability of machine parts is one of the main problems in the Ukrainian engineering industry, in particular for municipal sweeping machines [1, 2]. In order to clean the road surface from contaminants, municipal machines with brushing equipment are widely used. The most widespread brushing equipment is cylindrical brushes with a pile of polymeric material. During operation, the bristles of a cylindrical brush undergo intensive wear by interacting with the working surface containing abrasive particles, while its elastic characteristics change, which requires an increase in the required clamping force to maintain the most rational value of the contact patch width in order to ensure high quality cleaning and minimal bristle wear. Based on the analysis of statistical data, the vehicle fleet of municipal enterprises in Khmelnytskyi region experienced a slight decrease in the level of wear and tear from 2015 to 2020, despite the measures taken, from 63% to 59% [3, 4]. According to the Resolution of the Cabinet of Ministers of Ukraine No. 265 [5], one of the main tasks is to ensure the use of modern and highly efficient garbage trucks by the country's municipal enterprises, which are key in the collection, transportation and primary processing of municipal solid waste (MSW). This task, in particular, is facilitated by expanding the functionality of the garbage truck by equipping it with a mounted sweeper. This generally helps to improve the overall reliability of utility companies' operations, while solving various environmental issues. Planning for the renewal, maintenance and repair of municipal equipment is facilitated by establishing the regularity of wear of the cylindrical brush of the garbage truck's mounted sweeping equipment depending on its rotation frequency.

Analysis of recent research and publications

Paper [6] considers the technology for maintaining the city's street and road network during the period with positive air temperature, outlines methods for planning and determining the volume of cleaning work, provides technical characteristics of cleaning machines and a method for calculating their number. The article describes the characteristics and composition of garbage on the roadway of city streets and roads, its fractional composition, the content of dusty particles by fractions in the air above the road surface, the concentration of the main and most harmful elements of road dust, changes in the composition of garbage during the year, and the estimated annual accumulation of street garbage for Ukrainian cities per 1 m^2 of the road surface. The main factors influencing the performance of sweeping machines for cleaning the city's street and road network are determined. The performance of sweeping machines, factors influencing their performance and its calculation are considered. The modes of road surface cleaning (frequency), the intensity of garbage accumulation on the road surface and its contamination depending on the traffic intensity are also considered.

Measures aimed at significantly improving the efficiency of the technological process of road pavement cleaning are described in the paper [7]. These measures are aimed at reducing the need for cleaning equipment and manual labor, improving the sanitary, hygienic, aesthetic, transport and operational condition of the road surface in urban areas. It is noted that the elastic modulus of road pavement of intra-quarter passages should be at least 125 MPa, and sidewalks and pedestrian alleys over 3 meters wide should be no more than 85 MPa. If the humidity of the garbage is up to 20%, it is recommended to use sweeping machines with additional moisture with a humidity of less than 15%, and if the humidity of the garbage is more than 20%, it is recommended to use water washers.

The results of analyzing a set of partial indicators, such as fuel consumption for operation, work performance, maintenance and repair costs for brush equipment elements, as well as the cost of cleaning a certain area of roads or urban areas, are considered in the study [8]. These indicators allow us to estimate the efficiency of using municipal sweeping machines with brush equipment. The paper shows a functional diagram for the formation of a generalized efficiency criterion and proposes a mathematical expression for its calculation. An expression for determining a generalized criterion for the efficiency of using municipal machines based on the selected aggregation function is also obtained. For a clear presentation of the relationships between the factors that influence the partial indicators of efficiency of the use of municipal sweeping machines, a functional scheme for the formation of a generalized efficiency criterion of the work is proposed.

A study by modeling brushes using the finite element method to create a system for automating the road sweeping process is presented in the paper [9]. Taking into account the type of garbage and road conditions, it is noted that the driver of a sweeping machine needs to adjust the vertical pressure, angle of inclination, and speed of rotation of the curb brush, as well as frequently monitor the results of sweeping. The driver's work becomes more complex as he or she needs to carefully control the machine and perform sweeping operations at the same time. In the past, achieving efficient road sweeping has been problematic, including the reason of the unknown basic characteristics of the sweeping brushes. In this paper, a finite element model is used to analyze the deformation of metal brushes as they are pressed and rotated on the road. The key brush parameters considered include tooth length, width, and thickness, tooth radius, tooth angle and orientation, as well as the number of teeth per cluster, number of clusters per row, and number of rows. The brush teeth were modeled as thin cantilever beams using the commercial software package FE ANSYS. With this model, important brush characteristics such as force-strain ratio, contact pattern, and torque were obtained. The effect of different tooth geometries on the brush characteristics was also analyzed.

In the paper [10], it is noted that the use of brush seals can help improve engine performance by reducing losses. Brush seal wear models provide methods for predicting wear and costs. However, existing models do not systematically account for rotor eccentricity, radial deformation, and the effect of bristle hysteresis, which can lead to significant errors in some situations. Tests were conducted to study the effect of rotor-stator eccentricity and radial deformation on the wear process and flow characteristics of the brush seal. During the tests, the air leakage rate was measured at different times and operating conditions, and the eccentricity and radial deformation were measured using eddy current sensors. The test results showed that eccentricity and radial deformation have a significant impact on wear and flow efficiency. In the theoretical study, the abrasive wear equation was used to describe the loss of pile material, and a simplified description was used to express the eccentric rotor-stator motions. A wear model for the brush seal was developed, taking into account rotor-stator eccentricity and radial deformation, in which the hysteresis effect is observed. This model was validated using brush seal test data, and the results showed that there is an error of 20% compared to the calculated wear loss when rotor eccentricity, radial deformation, and hysteresis effect are fully considered.

The work [11] is dedicated to taking into account the interaction of forces, temperature effects on friction and wear of the brush pile, as well as establishing quantitative characteristics that affect the life and efficiency of the sweeping process, depending on the properties of the removed garbage and operating modes. The developed and implemented computer simulation model of the functioning of the brush unit of a municipal sweeping machine allows predicting the characteristics of the process and identifying their cause-and-effect relationships with the brush parameters and operating modes. The simulation model makes it possible to predict the service life and performance of the brush at the early stages of designing the brush body of a municipal machine, taking into account the model conditions of the subsequent application. The parametric adjustment of the simulation model was carried out by matching the calculated and experimental values of brush pile wear obtained in the field. The criteria characterizing the intensity of brush pile wear were established. It is found that the main reason that does not allow achieving improved operating modes of municipal machines is the limitation of the brush rotation frequency and heating of the contact surface of the pile, which leads to a decrease in the mechanical properties of the pile material and an increase in the intensity of its wear.

The problem of improving the quality of road surface cleaning and the service life of brushing equipment is discussed in [12]. Improving the quality of cleaning and the service life of brushing equipment will help reduce the cost of municipal equipment. During operation, the pile of a cylindrical brush wears out, which leads to a change in its elastic characteristics. This is reflected in the need to apply the optimal pressing force to ensure the optimal width of the contact patch, which guarantees high quality cleaning and minimal pile wear. The article presents the dependence of the degree of wear of the brush pile of brush working equipment on the actual radius of the cylindrical brush. The influence of the degree of wear on the elastic characteristics of the brush working equipment is also considered. The dependence of the average stiffness coefficient on the degree of wear of the cylindrical brush bristles, as well as the value of the required clamping force on the degree of wear at different values of the width of the contact patch of the cylindrical brush, is given. Also, the dependence of the pressure in the hydropneumatic accumulator of the brush working body position control device on the actual free length of the cylindrical brush pile was obtained.

Regression analysis was used to establish regularities that describe and predict the wear and tear of garbage trucks in Khmelnytskyi region in a scientific article [13]. In addition, the results of this analysis can help to develop a strategy for the infrastructure of municipal enterprises, such as the composition and renewal of garbage trucks, the creation of a production base for maintenance and repair, which is necessary to solve the problem of solid waste management.

An improved mathematical model of the functioning of the mechanism of solid waste dewatering in a garbage truck that takes into account the wear of the auger is presented in a scientific article [14]. This model made it possible to conduct numerical studies of the dynamics of the mechanism during its startup and determine the effect of auger wear on the performance characteristics of the device. The results of the study showed that with an increase in the degree of wear of the auger, the pressure of the working fluid at the inlet of the hydraulic motor of the mechanism increases, while the angular velocity and rotational speed of the auger significantly decrease at a constant flow rate of the working fluid. The dependences of these parameters on the degree of auger wear were expressed as power functions. Additionally, it was found that the wear of the auger by 1000 microns leads to an increase in the energy consumption of the MSW dewatering process by 11.6%, which, accordingly, increases the costs of this process in the garbage truck and accelerates the process of auger wear.

Paper [15] identifies adequate laws, according to the Fisher criterion, that describe the effect of cylindrical brush wear on the performance characteristics of the garbage truck's mounted sweeping equipment. It was found that, according to the Student's criterion, among the studied factors of influence, the degree of wear of the cylindrical brush has the greatest effect on the value of the deformation of the cylindrical brush, and the width of the contact patch has the least effect. The required clamping force of the cylindrical brush is most affected by the width of the contact patch, and the degree of wear of the cylindrical brush is the least. The response surfaces of the target functions - the values of the deformation and the required clamping force of the cylindrical brush and their two-dimensional sections in the planes of the impact parameters - are shown, which allow us to clearly illustrate the specified dependencies of these target functions on individual impact parameters. It is established that the degree of wear of a cylindrical brush of 50% leads to an increase in the deformation of the cylindrical brush by 1.3 times, and the required clamping force of the cylindrical brush by 3.1...3.6 times, depending on the width of the contact patch.

However, the authors did not find any specific mathematical dependencies describing the wear regularity of the cylindrical brush of the garbage truck's mounted sweeping equipment depending on its rotation frequency as a result of the analysis of known publications.

Aims of the article

Investigation of the effect of the rotational speed of a cylindrical brush of a garbage truck's mounted sweeping equipment on its wear.

Methods

The determination of the pairwise regularity of the wear of a cylindrical brush of the garbage truck's mounted sweeping equipment on its rotation frequency was carried out by regression analysis. The regression was determined on the basis of linearization transformations that allow us to reduce the nonlinear dependence to a linear one. The coefficients of the regression equation were determined by the least squares method using the developed computer software program "RegAnaliz", which is protected by a certificate of copyright law.

The results

The values of the two-week period of wear of a cylindrical brush of the mounted sweeping equipment of a garbage truck at different values of its rotation frequency are shown in Table 1 [11]. It was established for a contact area of 2x2.38 mm^2, pressure in the contact of 0.2462 MPa.

Table 1

Wear of the cylindrical brush of the garbage truck's mounted sweeping equipment at different values of its rotation frequency [11].

№	Rotational speed of a cylindrical brush *n*, sec^{-1}	Cylindrical brush wear, mm
1	25.89	2
2	37.75	1.5
3	43.55	25.3
4	49.77	77.2
5	62.21	200

As a result of the regression analysis of the data in the Table 1, the regularity of wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on the frequency of its rotation was determined

$$u = 0.4593 + 1.834 \cdot 10^{-8} n^{5,6} \text{ [mm]}, \quad (1)$$

where u is the wear of the cylindrical brush, mm; n is the rotational speed of the cylindrical brush, sec^{-1}.

The obtained regularity (1) can be used to create a mathematical model of the operation of the hydraulic drive of the improved mounted sweeping equipment of a garbage truck, taking into account the wear of its working bodies.

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

Table 2

Results of regression analysis of the dependence of wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on its rotation frequency

№	Type of regression	The correlation coefficient R	№	Type of regression	The correlation coefficient R
1	$y = a + bx$	0.90344	9	$y = ax^b$	0.88698
2	$y = 1 / (a + bx)$	0.75548	10	$y = a$ + b-lg x	0.83080
3	$y = a + b / x$	0.74532	11	$y = a$ + b-ln x	0.83080
4	$y = x / (a + bx)$	0.64049	12	$y = a / (b + x)$	0.75548
5	$y = ab^x$	0.91040	13	$y = ax / (b + x)$	0.72063
6	$y = ae^{bx}$	0.91040	14	$y = ae^{b / x}$	0.84135
7	$y = a$ -10^{bx}	0.91040	15	$y = a$ -$10^{b / x}$	0.84135
8	$y = 1 / (a + be\ )^{-x}$	0.45308	16	$y = a + bx^n$	0.99115

It has been established that the wear of a cylindrical brush of the garbage truck's mounted sweeping equipment increases according to a power law with an increase in its rotation frequency.

For a Ukrainian-made sweeping machine of the serial model KO-713-01, which is equipped with a cylindrical brush with a rotation speed of 3200 rpm, its wear according to the obtained dependence (1) will reach the following value:

$$u = 0.4593 + 1.834 \cdot 10^{-8} \left(\frac{3200}{60} \right)^{5,6} \approx 86.5 \text{ [mm]}.$$

Fig. 1 shows the graphical dependence of the change in wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on its rotation frequency, that was built using the dependence (1), which confirms the sufficient convergence of the obtained dependence at the level of 0.99115 compared to the data given in the Table 1.

From Fig. 1 it can be seen that reducing the rotation frequency of the cylindrical brush of the garbage truck's mounted sweeping equipment from 62 sec^{-1} (3700 rpm) to 26...38 sec^{-1} (1550...2250 rpm) leads to a decrease in its wear by 2 orders of magnitude, which indicates the importance of identifying further ways to increase its wear resistance.

Consideration of the effect of contact area and pressure in the contact on wear, as well as the development of recommendations for the selection of wear-resistant brush pile materials for the garbage truck's mounted sweeping equipment, require further research.

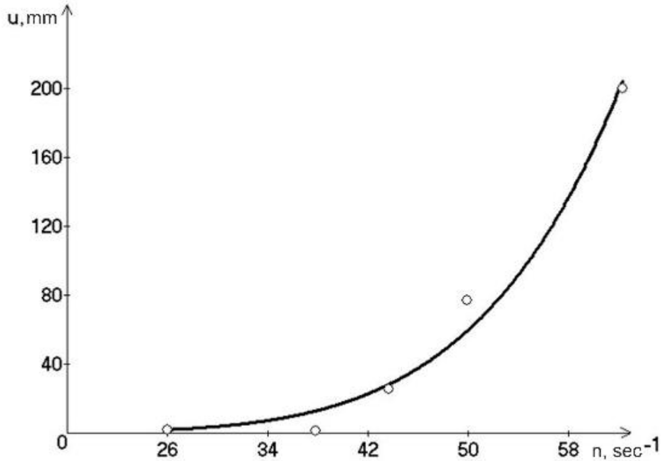

Fig. 1. Dependence of the change in wear of the cylindrical brush of the garbage truck's mounted sweeping equipment on its rotation frequency: actual ○, theoretical –

Conclusions

In the paper it is established a power law of change in the wear of the cylindrical brush of the garbage truck's mounted sweeping equipment with its rotation frequency, which can be used to create a mathematical model of the hydraulic drive of the improved mounted sweeping equipment of a garbage truck, taking into account the wear of its working bodies. It has been determined that for a Ukrainian-made sweeper of the serial model KO-713-01, which is equipped with a cylindrical brush with a rotation speed of 3200 rpm, its wear will reach 86.5 mm according to the obtained dependence. Therefore, taking into account the effect of the contact area and pressure in the contact on wear, as well as identifying further ways to increase the wear resistance of the cylindrical brush of the garbage truck's mounted sweeping equipment, requires further research.

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Березюк О.В., Савуляк В.І., Харжевський В.О., Семічаснова Н.С., Гарбуз Є.С. Встановлення закономірності зносу циліндричної щітки навісного підмітального обладнання сміттєвоза від частоти її обертання.

Стаття присвячена встановленню закономірності зносу циліндричної щітки навісного підмітального обладнання сміттєвоза від частоти її обертання. Використання математичного апарату та відповідних програм регресійного аналізу дозволило визначити степеневу закономірність зміни зносу циліндричної щітки навісного підмітального обладнання сміттєвоза від частоти її обертання, яка може бути використана під час побудови математичної моделі роботи гідроприводу вдосконаленого навісного підмітального обладнання сміттєвоза із урахуванням зносу його виконавчих органів. Побудована графічна залежність зміни зносу циліндричної щітки навісного підмітального обладнання сміттєвоза від частоти її обертання, яка підтвердила достатню збіжність отриманої закономірності. Графік впливу частоти обертання циліндричної щітки навісного підмітального обладнання сміттєвоза на її знос демонструє доцільність її зниження. Встановлено, що для підмітальної машини українського виробництва серійної моделі КО-713-01, яка оснащена циліндричною щіткою з частотою обертання 3200 об/хв, її знос за отриманою закономірністю досягатиме 86,5 мм. Виявлено, що зменшення частоти обертання циліндричної щітки навісного підмітального обладнання сміттєвоза з 62 $с^{-1}$ (3700 об/хв) до 26...38 $с^{-1}$ (1550...2250 об/хв) призводить до зниження її зносу на 2 порядки. Встановлена доцільність проведення додаткових досліджень з виявлення подальших шляхів підвищення зносостійкості циліндричної щітки навісного підмітального обладнання сміттєвоза.

Ключові слова: знос, частота обертання, навісне підмітальне обладнання, циліндрична щітка, сміттєвоз, закономірність, регресійний аналіз.

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Analysis of tribological aspects during operation and repair of internal combustion engine valve mechanism parts

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Abstract

The problem of researching mechanisms of wear of valve mechanism parts remains very relevant due to the need for constant improvement of the design and increase in durability of internal combustion engines. The paper provides an overview of modern research on the following issues: analysis of operating conditions and malfunctions of the valve mechanism of the internal combustion engine, research on friction and wear of valve mechanism parts, repair and restoration technologies, increasing the wear resistance of engine valves, modeling, calculations of valve mechanism parts. It is shown that an important aspect for the analysis of the wear resistance of valve mechanism parts is the operating conditions and the nature of damage to the surfaces of the friction pair parts. The existing hypotheses about the mechanisms of friction, lubrication and wear of valve mechanism parts are considered, the designs of test stands are given, and the results of tribological tests are analyzed. It is substantiated that the technological methods of surface engineering are becoming an increasingly viable alternative to structural changes to improve the performance of valve mechanism parts. An overview of calculation methods for assessing the stress and thermal state of valve mechanism parts of internal combustion engines is provided.

Keywords:internal combustion engine, valve, guide, damage, restoration, wear resistance, modeling, finite element method

Introduction

The engine valve is a responsible part of every internal combustion engine and gas distribution mechanism. The valve mechanism is responsible for the harmonious operation of the engine, controlling the quality of the following processes: timely supply of fuel to the combustion chambers, removal of spent fuel - exhaust gases.

The main principle of operation of the engine valve is to create the necessary hermetic conditions in the chamber at the moment when the fuel mixture ignition procedure takes place. During operation of the power unit, such parts are subjected to special loads. The number of valves depends on the specific engine. Most often, engines with four valves are installed in modern vehicles: two intake and two exhaust.

Automotive engine valves must meet the following characteristics:

1. Ensure a hermetic connection in connection with the saddle.
2. Do not be negatively affected by corrosion even when moisture gets inside.
3. Provide high resistance to shock loads, mechanical damage during operation.
4. Provide effective heat transfer.
5. To have a small weight, without creating an additional load on the unit, to be a strong, rigid part.

The valve mechanism consists of a spring made of steel, a seat, a sleeve and a mechanism responsible for fixing the rotary device. During operation of power units, the base of the exhaust mechanism is exposed to high temperatures up to 500-700 degrees.

As a result of valve guide wear, the following valve damage and sealing problems may occur: burnt valve heads; cracks in the valve stem; cracks in the grooves for valve crackers; excessive wear of valve stem ends; worn on one side of the rocker arm; increased oil consumption due to wear of valve stem seals; worn or burnt valve seat rings.

If there is too much clearance or uneven, conical or tubular wear, the valve guides must be replaced. Deformed valve guides strongly affect valves with a stem diameter of less than 8 mm. If the guide is deformed, the valve head is off-center on one side of the valve seat and is pulled into the seat by the force of the valve spring. After some time, this can lead to valve failure. Under the action of the variable load that occurs during bending, the valve breaks at the junction of the rod and the valve head. When using rocker arm or balancer actuated valves, deformed valve guides cause increased radial force to be applied to the valve stem. As a result, the valves break in the area of the groove for the valve wedges. The problem of researching mechanisms of wear of valve mechanism parts remains very relevant due to the need for constant improvement of the design and increase in durability of internal combustion engines. In this work, a review of the results of modern research on the wear resistance of the parts of the valve mechanism of various engines in operational and laboratory modes of operation is carried out. The review was carried out in the following directions: analysis of operating conditions and malfunctions of the valve mechanism of the internal combustion engine, research of friction and wear of valve mechanism parts, repair and restoration technologies, increasing the wear resistance of engine valves, modeling, calculations of valve mechanism parts.

Analysis of operating conditions and malfunctions of the valve mechanism of the internal combustion engine

An important aspect for analyzing the wear resistance of valve mechanism parts is the operating conditions and the nature of damage to the surfaces of the friction pair parts. Research [1] is focused on different failure modes of internal combustion engine valves. The closed valve is loaded by the force of the spring and the pressure inside the cylinder, which periodically changes during engine operation and reaches a peak value of the order of 15 MPa. This high pressure inside the cylinder causes the valve cone to bend, resulting in slippage and improper contact between the valve face and the seat insert, ultimately leading to wear.

Exhaust valves operate at very high temperatures and are subjected to cyclic loads. The failure of the conical valve surface is mainly caused by elastic and plastic deformation and fatigue. The exhaust valve stem usually fails due to overheating as the temperature of the exhaust valve is around 720 ºC.

At high loads, multiple cracks are initiated if the valves are exposed to high temperatures, and under these operating conditions it would be logical to expect failure to occur within several million cycles. The broken valve stem is shown in Fig. 1.

Fig. 1. The edge of the fracture surface of the valve stem

Considerable hardness is lost due to overheating and surface oxidation and galling of the valve stem occur. Fatigue properties of the alloy suffer from high temperature. This is the reason for the initiation of multiple fatigue cracks. Faulty exhaust valves are shown in fig. 2.

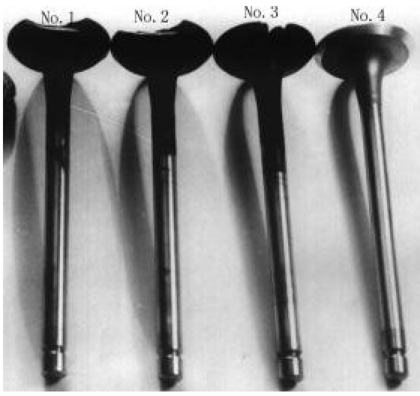

Fig. 2 General appearance of valve damage

It has also been found that wear usually occurs on the valve seat surface and on the stem due to sliding within the stem guide. The rate of wear increases with the number of cycles. Erosion-corrosion failure of exhaust valves is also a recognized failure mode of internal combustion engine valves.

An analysis of exhaust valve failures was carried out in [2].diesel engine. A visual inspection of the damaged engine parts showed that the fracture of the exhaust valve showed signs characteristic of fatigue failure. Additional observations of the crack initiation zones showed that the origin of the crack was not covered by material defects orcorrosion products. Nonlinear finite element analysis was used to explain the cause of premature valve failure. The results of the stress analysis performed on the soot valve showed that high bending stresses occur in the valve stem.

The car had a diesel engine failure with a mileage of 230,000 km. Damaged 4-cylinder turbocharged piston engine, fatigue failures of exhaust valves in this engine occurred at significantly higher mileage (600-900 thousand km).

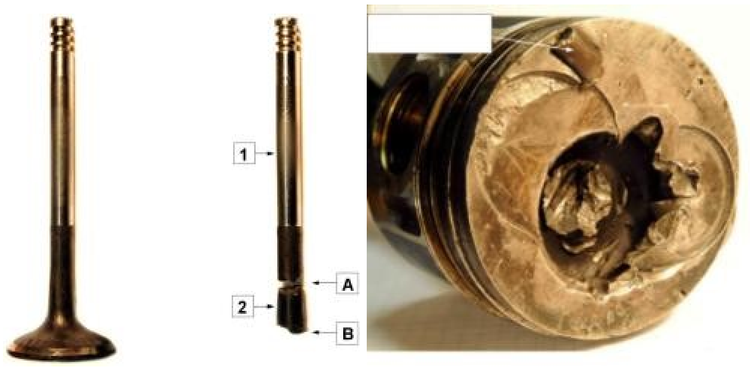

Fig. 3. View of the details of the damaged diesel engine valve

After the breakdown, the engine was disassembled. A piece of the exhaust valve was found in the engine head (part No. 1, Fig. 3). The second piece of the damaged valve (part #2, Fig. 2) was driven into the upper surface of the piston. In fig. 3 shows the depressions formed after the collision of the broken valve head with the piston. The third piece, the damaged valve (head), was lost during the engine repair, so it is not shown. Therefore, the problem of the destruction of the exhaust valve of the diesel engine was investigated. A visual inspection of the damaged valve revealed that fatigue cracks had formed in the valve during engine operation.

Gasoline direct injection (GDI) engines have a well-known tendency to develop intake valve deposits (IVDs), regardless of operator maintenance, engine architecture, or cylinder configuration [3]. The process of deposit formation is not sufficiently studied and there is no standardized engine test to study the effect of variable fuel composition or lubricants.

Since the fuel is injected directly into the combustion chamber and not into the intake valve like in PFI engines, there is no longer the washing action of the fuel and the cleaning additives contained in the fuel to keep the intake valves free of deposits. Possible intake valve deposits now build up steadily over time until they affect engine performance, often with disastrous results. In fig. 4 shows the direct fuel injection system with the position of the fuel injector relative to the intake valve.

Fig. 4. Direct fuel injection system

Due to the lack of a fuel flushing process, characteristic of engines with port fuel injection, deposits constantly accumulate over time and can lead to poor combustion, unstable operation, valve sticking or engine failure (Fig. 5). Vehicles using these engines often have to undergo expensive maintenance to mechanically remove the deposits that re-form over time. On a car equipped with a 2.0-liter GDI turbo engine, the mechanisms leading to the formation of deposits were studied and analyzed. It has been determined to be a combination of engine oil, engine wear, unburned fuel and exhaust pollutants. It was also found that the rate of accumulation is affected by the composition variables of the motor lubricant.

Fig. 5. Deposits on intake valves

The dynamic development of the design of internal combustion engines creates the need to introduce operation strategies based on information about their technical condition. The article [4] analyzed the problems associated with the vibration diagnosis of the valve gap of the internal combustion piston engine, which is significant from the point of view of efficiency and durability. Classification methods are proposed for evaluating valve clearance. Experiments aimed at providing information necessary for the development and verification of the proposed methods were performed and described. In the conducted studies, vibration signals were obtained from a triaxial accelerometer located in the head of the engine cylinder block.

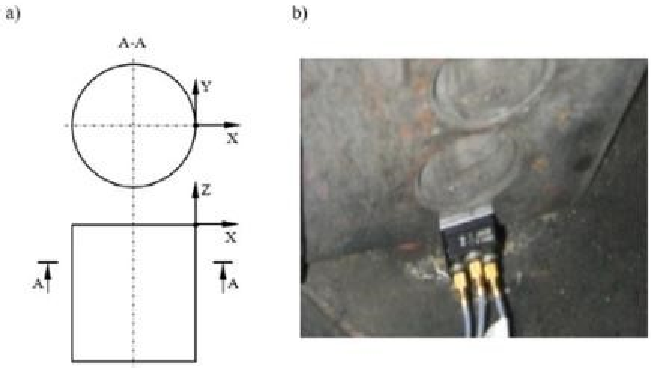

Fig. 6. a) Orientation of vibration measurement directions on the cylinder head, b) view of the vibration sensor installed on the cylinder head

The selection of the vibration measurement point (Fig. 6) was preceded by an analysis of the design of the cylinder head, studies related to the determination of the influence of the valve clearance of the diesel engine on the selected vibration parameters. The received vibration signal was parameterized for the engine operating under different engine loads, rotation frequency and valve clearance settings. The parameterization concerned the characteristics of vibration signals, the derivative of the vibration signal as a function of time, as well as the envelope of this derivative. Based on the conducted research and analysis, a methodology for assessing the valve gap is proposed.

In work [5] malfunctions of automobile valves were considered. Changes in valve microstructure were studied and analyzed using a scanning electron microscope (SEM). Samples were made from failed engine valves, while new valves were also analyzed for comparison. This was done by analyzing images of defective and new valve samples at sufficient magnification. A comparative analysis of the microstructures of defective valves and new valves showed that the grain size and distribution of carbide particles in the material matrix are affected by high temperature conditions. The microstructure of the valve material shows noticeable changes after working at high temperatures. The grain size of the material also changes at high temperature, which reduces the hardness of the valve material and causes more wear.

The article [6] presents an analysis of elements of internal combustion piston engines that interact with the combustion chamber. An assessment of the state of tribological nodes: valve stem - valve guide and valve head - valve seat in random operating conditions was carried out. The image of wear and damage of parts of tribological nodes was studied (Fig. 7).

Fig. 7. Pathological wear of the guide part of the intake valve stem from the head side

Analysis of digital images of real objects was carried out using an optical microscope and measurement of macro- and microgeometry. Identification of the main wear processes was carried out.

Study of friction and wear of valve mechanism parts

In the article [7], he proposed a multifunctional device for determining wear for the study of tribological characteristics of connections of the valve mechanism of the engine (Fig. 8). The device uses a mechanical load system, which consists of a special eccentric wheel and disk springs that simulate the load from the engine combustion chamber, as well as simulate the contact loads of the valve mechanism elements. The test bench has three functions for different studies using specially designed instruments. The first function aims to evaluate the interaction between the valve seat surface and the seat insert at high temperatures and loads. The second function is used to investigate the friction and wear properties of the valve stem and valve guide. The third function is designed to evaluate the performance of valve seals. Tests were conducted using the proposed experimental complex. It was established that the wear mechanisms occurring in the studied friction pairs are a combination of oxidative wear, adhesive wear, and fatigue delamination.

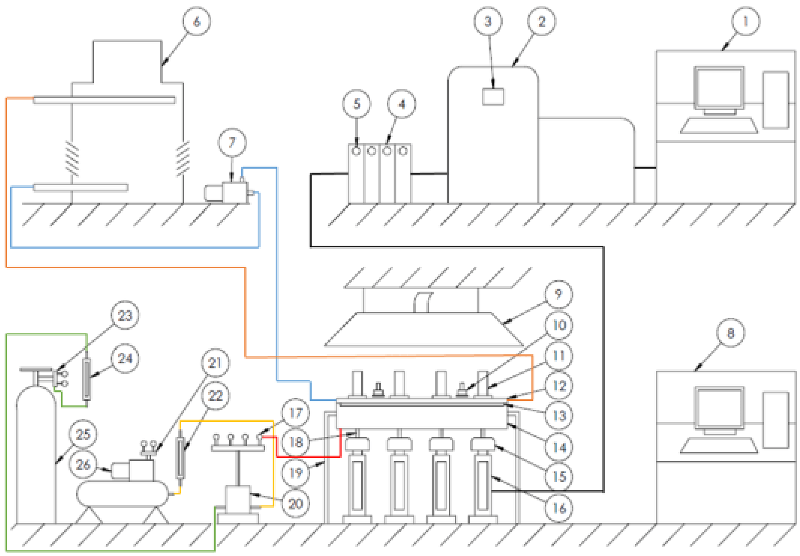

Fig. 8. Experimental complex of tests of friction pairs of the internal combustion engine valve mechanism: 1 - hydraulic control system, 2 - hydraulic pump, 3 - hydraulic control panel, 4 - oil pressure in the hydraulic accumulator system, 5 - pressure indicator, 7 - pump cooling system, 9 - exhaust system, 10-rotor valve, 15- strain gauges, 16- hydraulic drives, 19- stand for testing holders, 20- gas mixer, 25- cylinder, 26- compressor

In fig. 9 shows the results of SEM analysis on the valve surface. After the tests, no signs of cracks or corrosion pits were observed. Quantitative analysis using energy dispersive spectroscopy (EDS) was performed on different areas of the valve surface.

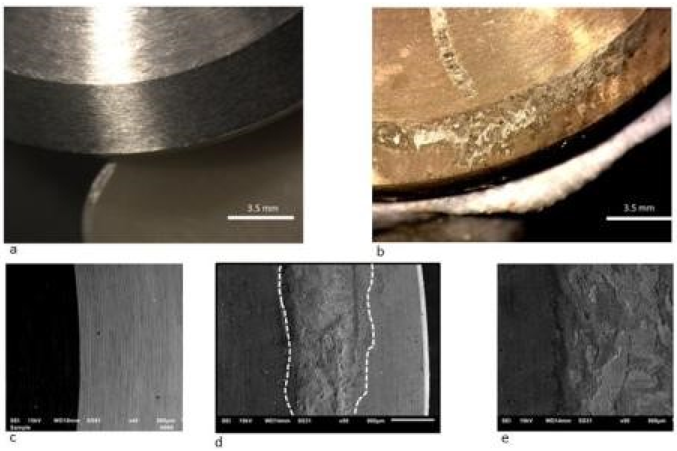

Fig. 9. Microscopic analysis of the valve surface before and after the tests

As a result of repeated loads and high temperature, the valve seat material became detached and adhered to the valve surface. This was confirmed by microscopy when additional material was observed attached to the valve surface (Figures 9a and 9b). A stellite coating was preserved on some parts of the valve surface (Figs. 9d and 9e).

A lightweight valve is often made of TiAl alloys, and its stem can be solid or hollow. Such valves can be connected to guides made of cast iron or phosphor bronze under different conditions in the contact zone. The purpose of the study [8] was to measure the frictional force in the sliding contact between a valve stem made of TiAl alloy and its guide made of phosphor bronze in the absence of oil. The load on the contact zone changed periodically during the series. During the tests, the displacement and acceleration of the valve were measured, as well as the force when it hit the saddle insert. In addition, the sound level was measured. Tests were conducted for different frequencies of the driving force. In addition, research was carried out on a pin-on-disc tribotester with a pin made of Ti6Al4V alloy and a disc made of phosphor bronze. A model of a research stand for modeling the dynamics of a rotating plate assembly of a material sample has been developed. The purpose of such studies was to obtain values of the coefficient of friction for such a tribological/ The article presents the obtained dependences of the coefficient of friction on the load, sliding speed, and duration of movement of the material sample.

Growing requirements of environmental legislation are changing the operating conditions of the valve mechanism in heavy-duty engines. Increased pressure, higher temperatures and a smaller amount of soot that can form a protective film are the main problems in these mechanisms. Three pairs of valves and valve seat inserts with the same material and structural properties, but with different operating conditions, were analyzed in [9] to investigate the wear process. The identified wear mechanisms were a combination of oxidation and adhesive wear, which was observed in the form of material transfer. Tribofilms with a thickness of 1 to 5 μm, consisting of Ca, O, P, S, and Zn, were found on the surfaces of the sample. The film in all cases protected the surface from wear, but in some cases it had a corrosive effect.

The efficiency of the valve mechanism of the engine largely depends on the valve guide. The choice of material is influenced by the extended life of the engines, which favors the use of casting and finishing materials such as cast iron. The purpose of the study [10] is to study the dry sliding characteristics of GG25 cast iron with copper additives. It has been established that changes in load and sliding speed affect the wear characteristics is of primary importance. The loads varied by 30 N, 40 N and 50 N, maintaining a constant speed of 1 m/s. Next, the sliding speeds of 0.5 m/s, 1 m/s, and 2 m/s were changed, maintaining a constant load of 30 N. In the course of the research, friction forces and the friction coefficient were also determined. The wear mechanisms of the samples were checked using a scanning electron microscope in combination with EDX analysis. The study highlights the significant influence of normal load and sliding speed on wear. In conditions of moderate load and speed, the influence of normal load is more significant. However, as sliding accelerates, it becomes the dominant factor. The analysis of friction forces and the coefficient of friction showed that under load conditions of 30 N–50 N, the coefficient of friction increased from 0.238 to 0.43.

In addition to the problems of valve guide wear, one of the most common problems is the study of valve seat wear, which researchers pay a lot of attention to. In [11], an experimental approach to solving valve and seat wear problems is described. The test bench contained sample valves and seat inserts simulating combustion loads and a cylinder head to study the impact effect on valve closing without applying combustion loads. Bench tests make it possible to evaluate the impact of changes in design and operating parameters with less time spent than when testing an engine.

Valve wear has been a problem for engine designers and manufacturers for many years. Although new valve materials and manufacturing techniques are constantly being developed, these advances are outpacing the demands for increased engine performance. The objective of [12] was to establish the effect of engine operating parameters on diesel engine intake valve wear and to test seat materials using test equipment designed to simulate load environments and contact conditions. Valve wear has been shown to increase with combustion load, valve closing speed, and valve displacement. Two of the tested materials have increased wear resistance. These are martensitic aging steels and ductile cast irons. Both showed significantly higher wear resistance than other tested materials.

In [13], the wear of the seating surfaces of the exhaust valve and the seat insert was investigated, which affects the engine performance depending on the mileage (number of cycles). All other parameters such as temperature (350 °C), fuel (LPG) and load (1960 N) were fixed. Exhaust valves and seat liners were used as test specimens. Tests with showed that the average maximum valve roughness increased at a rate of 7.76 μm/106 cycles. The products of the tribochemical reaction coated the metals of the valve and seat inserts, preventing wear, and included O, V, S, and Al. The wear mechanism of the valve and seat insert was investigated using a tribochemical reaction.

Engine valve seat wear affects engine performance. Improving valve quality and valve life is a common goal for both valve and engine manufacturers. By performing tests on a valve seat wear simulator, [14] investigated the effects of cycles, load, and temperature on intake valve seat wear. Test temperatures ranged from 180 to 650 °C, number of cycles varied from 150,000 to 3,420,000, and test loads were applied from 6,615 to 24,255 N. The relationship between valve seat and insert wear as a function of cycles, load, and temperature was determined experimentally. . A load-dependent wear transition was found to exist, implying different wear mechanisms operating in these different regions. Higher temperatures resulted in less saddle wear. Inlet valve seat/insert wear mechanisms were found to be a complex combination of adhesion, shear deformation, and abrasion. Oxide films formed during testing were found to play a significant role. They can prevent direct metal-to-metal contact and reduce friction and wear.

Ball reciprocating tests on a flat surface were performed on prepared sections cut from cast iron, silicon nitride, and composite graphite valve guides over a given range of temperatures, normal loads, speeds, and lubrication conditions [15]. The goal was to find out if the ceramic composite would create a lubricating film on the surface and serve as a self-lubricating material. Stainless steel type 440C was used as the counterbody material. Tests were also performed using graphite powder on a silicon nitride matrix material to determine what frictional behavior could be observed in the most favorable case. Friction and wear data combined with surface chemical analysis confirmed that the current composite, despite its wear resistance, does not provide any lubrication benefits over silicon nitride itself.

Lightweight valves are commonly used in modern internal combustion engines with cam and camless camshafts. They can be made of TiAl and Ti6Al4V alloys. The stems of such valves can be covered with a protective layer obtained by nitriding, chrome plating or others. Rods can be connected to guides made of cast iron, phosphor bronze or beryllium bronze. Coupling can occur under conditions of mixed friction with a different proportion of lubricant. Research of the valve mechanism was carried out in a tribotester [16].

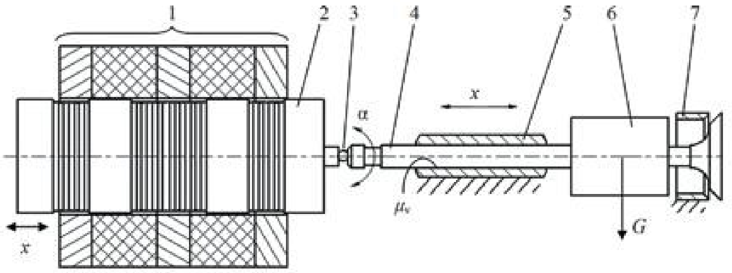

Fig. 10. Unit model: 1 – fixed part of the drive, 2 – moving coil, 3 – hinge, 4 – valve, 5 – guide, 6 – additional load, 7 – seat insert

A model of the unit was developed (Fig. 10), which consisted of valve 4 and a moving coil 2 of the actuator and is presented in Fig. 3. The displacement x of such a coil parallel to the axis of the stationary part 1 of the drive was assumed to be equal to the displacement of the valve obtained during its measurement in the tester. Such displacement is limited by the settlement of the seat insert 7. The valve is loaded with an additional weight 6, which causes a force G, perpendicular to the axis of the guide 5. The valve can also wobble by an angle α, within the limits limited by the gap between the valve stem 4 and its guide 5. Such wobble is allowed due to the presence of a spherical joint 3.The studied valve was set in electromagnetic motion for different strokes and frequencies of the valve. Contact took place in the absence of oil. The valve was loaded with additional mass to create a normal force between the valve stem and its guide. The acceleration and displacement of the valve, the impact force of the valve on the seat insert, the friction force between the valve stem and its guide and the sound level were measured. The purpose of the research is to obtain and compare the values of the coefficient of friction between the cast iron guide and the Ti6Al4V valve stem for a certain number of valve strokes and frequency. The leg under study can be bare or covered with a layer of Cr or nitriding. An analytical model was developed to calculate the contact pressure and friction force between the valve stem and its guide for the mixed friction conditions that occur for the selected engine oil and the movement of the valve relative to its guide.

In work [171], experiments were conducted using a high-temperature tribological test system (Fig. 11). For this experiment, an exhaust valve made of a nickel-based alloy called Pyromet was machined into a flat disc, and a sample pin was made of a Co-based alloy (Stellite). The pin had a spherical end with an initial radius of 9.53 mm and the test was carried out under a normal force of 1710 N at a sliding speed of 0.1 m/s. Sliding was performed for 60 seconds at each of the following temperatures: 450, 550, 650, 750, 800, 850 o C.

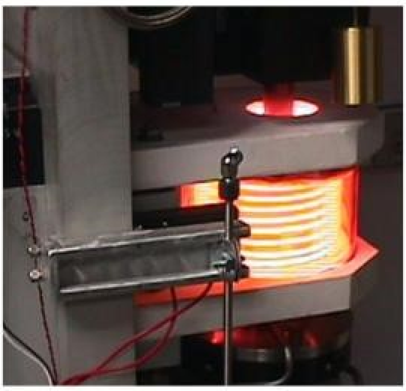

Fig. 11. High-temperature sliding friction and wear test system.

The growing demand for more powerful internal combustion engines has led to higher temperatures in the combustion chamber. As a result, TiAl valves have been investigated for use in a natural gas diesel internal combustion engine, taking advantage of their low density and high temperature resistance. In [18], comparative bench tests of traditional steel valves and TiAl valves were conducted using a specially designed apparatus for testing wear. Compared to traditional valves made of heat-resistant steel (X60, X85), TiAl valves have 50% less weight, which leads to a decrease in resistance during engine operation. By reducing the inertia of the engine valve movement, the dynamic characteristics of the engine valvetrain system can be optimized. Each contact pair of the valve and seat insert has been tested for 3 million impact cycles. Compared with the austenitic exhaust valves (X60) tested at 700℃, the TiAl valve had better wear resistance and the wear loss was reduced by 24.8%. The dominant wear mechanism is considered to be a combination of oxidative wear and adhesive wear. However, for the intake valves tested at 400℃, the wear loss of the TiAl valve was three times higher than the martensitic intake valves (X85). The predominant wear mechanism can be defined as abrasive wear and adhesive wear (Fig. 12).

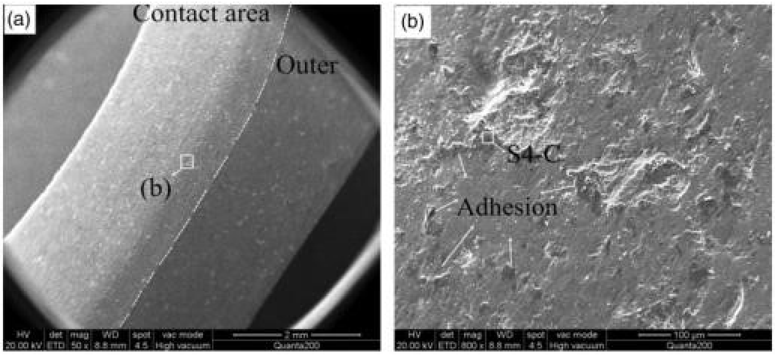

Fig. 12. (a) Worn surfaces of valve seat insert; (b) magnified image of worn surfaces and EDS S4-C test area.

Thus, it is concluded that the TiAl exhaust valve is a potential solution for a diesel engine running on natural gas.

Technologies of repair, restoration, increase of wear resistance of engine valves

The article [19] presents the results of tribological research on a promising method of restoring and increasing the wear resistance of engine valves by the method of gas nitriding. It was established that with increasing operating time, the guide bushings of the output connections wear out with the displacement of the axis of the form-forming surfaces of the hole. It has been proven that the uneven wear of the bushing hole is determined by the imbalance of the forces acting on the side of the rocker arm. Distortions of the valve in the longitudinal axis of the engine contribute to a decrease in the tightness of valve pairs. Technological means and methods of improving the quality of repair, measuring devices for accurate research of the parameters of parts and connections of the valve group are presented. A method of nitriding with an installation for its implementation has been developed, which provides an environmentally friendly method of low-temperature and high-temperature hardening, obtaining deeper and well-developed layers of the diffusion near-surface zone.

In an internal combustion engine, a system of valves controls the flow of gases into and out of the combustion chamber. The contacting surfaces are subjected to a severe tribological situation with high temperatures, high-velocity impacts, corrosive environments, and high clamping forces, causing micro-slip at the interface. Work surfaces must withstand hundreds of millions to billions of operating cycles, resulting in extreme requirements for low wear. Such low wear rates can be achieved due to the protective action of tribofilms formed from oil residues, avoiding pure metal-to-metal contact.

One way to combat random behavior may be to promote the reliable operation of protective tribofilms by texturing valve seal surfaces to improve grease capture and storage [20]. At the same time, depressions perpendicular to the slip are created (Fig. 13).

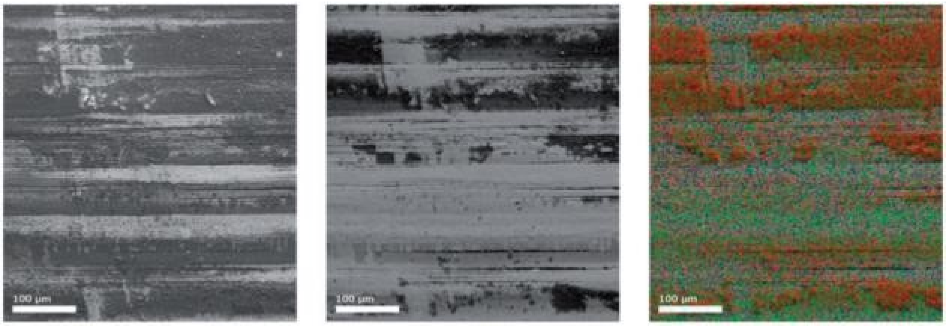

Fig. 13. Appearance of the textured surface of the valve after 100,000 cycles.

The number and localization of tribofilms became more stable than without texture, which led to a decrease in surface wear. For the same width, deeper depressions showed less delamination of the tribofilm.

Article [21] is devoted to the issues of friction, lubrication and wear of internal combustion engine parts, the improvements of which provide an important increase in energy efficiency, productivity and durability of internal combustion engine systems. The paper considers the process of reducing friction with surface textures or coatings. The paper also discusses surface engineering technologies such as diamond-like carbon coatings and surface texturing technology. Information is also provided on thermal spraying techniques that have led to improvements in engine parts. The wear of the piston unit, valve mechanism, cylinders, engine bearings is described. A detailed analysis of the wear mechanisms of the intake valve and seat of the internal combustion engine is given.

Since surface engineering is becoming an increasingly viable alternative to design changes made to increase the efficiency of internal combustion engines, various types of coatings for internal combustion engine parts have been proposed and tested in [22]. One of the vital organs is the engine valves, which during operation are subjected to combined thermal, mechanical, corrosion and wear, which lead to severe corrosion and complete failure. In this paper, the valve wear aspects were analyzed and the active surfaces were coated by atmospheric plasma sputtering (APS) with two commercial powders: Ni-Al and YSZ. A microstructural analysis of these layers was carried out, as well as observations regarding the possibility of their use as a thermal barrier and antioxidant coatings.

Modeling, calculations of valve mechanism details

The production of additive layers of metal components provides significant opportunities to reduce the weight of parts in order to increase the fuel efficiency or performance of the vehicle. In the article [23], filling materials are considered to reduce the weight of intake or exhaust valves of an internal combustion engine. Micro-computed tomography (μ-CT) was used to reverse engineer the original component and assess the internal geometry and material integrity of the valve (Fig. 14.).

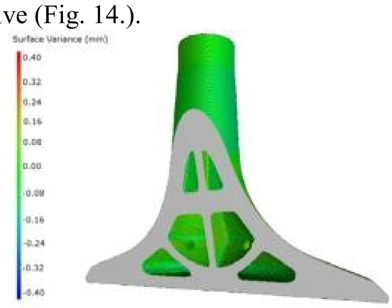

Fig. 14. Results of valve design analysis

The valve has been redesigned using Finite Element Analysis (FEA) to select a lightweight weighted design that provides a weight savings of 9.4g (20%) compared to the original equipment valve. The engine was tested for more than 175,000 cycles at 2,000 to 9,500 rpm, after which μ-computed tomography confirmed no signs of internal cracking, failure, or significant deformation.

The article [24] describes the concept of a non-invasive method for diagnosing the value of valve clearances in internal combustion engines, based on the analysis of engine surface vibration signals using artificial neural networks. The applicability of the method was tested on a single-cylinder compression-ignition engine with a low power rating, which had an indirect valve-acting valve timing mechanism and manually adjusted valve clearances. The method uses the readings of vibration sensors as diagnostic signals, which record the acceleration of the engine head depending on the angle of rotation of the crankshaft, with pre-set values of valve clearances measured in a cold state. Among the registered signals, the components corresponding to the impact of the rocker arms on the valve stems were identified, and low frequencies were filtered out in order to eliminate measurement interference. A classifier of selected features of the processed signals was built using artificial neural networks. This classifier recognizes signals generated by engines with the correct valve clearance, as well as engines with too much and too little valve clearance.

In the article [25], a study of the causes of engine intake valve damage was conducted, during which the intake valve heads were overheated and deformed as a result of material creep. On the example of a malfunction detected in the analyzed engine, it was established that traditionally known causes, such as a failure of the combustion process, cannot cause the described damage. In order to determine the real causes of damage to the intake valves, the authors simulated the thermal state of the intake valve under cooling conditions with the influence of gas in the cylinder and the influence of air in the intake pipeline, as well as contact heat exchange with the seat, taking into account the thermal conductivity along the stem. The calculations showed that with an increase in the rotation frequency, the failure of the control system leads to an increase in temperature higher than recommended for the materials used. Based on the conducted research, the authors have developed recommendations for increasing the reliability of intake valves with variable gas distribution phases.

In [26], a methodology for the analysis of valve wear of internal combustion engines is proposed, which is the result of the combined use of numerical and experimental methods. Numerical solutions are obtained using a specialized finite element method where a solution contact algorithm is used to model the flexible-flexible contact along with the adhesive wear law. Experimental results are obtained on a wear test rig specially designed to evaluate wear parameters under valve operating conditions. A good agreement was found between the experimental wear profiles and the numerical calculations of the wear on the contact surfaces.

In [27], engine reliability was improved using Al-Sic composites for engine guide valves. Aluminum matrix composites turned out to be the most suitable for the automotive industry. Finite element analysis of Al-Sic composite with titanium alloy (Ti-834), copper-nickel silicon alloys (CuNi3Si) and aluminum bronze alloy as alternative engine valve guide material was performed using Ansys 13.0 software. The finite element method is one of the most widely used methods for analyzing mechanical load characteristics in modern engineering components. The directional valve model was modeled as shown in Fig. 15. A finite element model was built to analyze the guide valve.

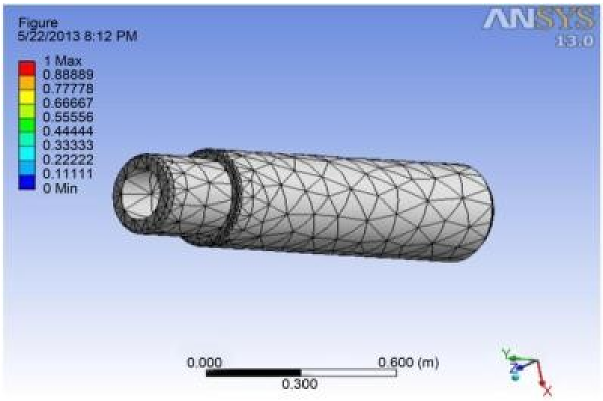

Fig. 15. Finite element model of the valve stem-guide bush connection

The stress analysis of the engine valve guide at different pressures and temperatures was carried out. The pressure is taken from 10 MPa to 100 MPa with different temperatures from 600°C to 650°C. It was found that the stresses were significantly lower than the allowable for all materials, but Al-Sic composites were found to be the most optimal.

In diesel engines, the valve seat contact is one of the few non-lubricated contacts subject to significant deterioration. This deterioration is confirmed by the removal of material on the intake valve. Wear and tear can lead to gas leaks and engine failure. The purpose of the work [28] was to determine the main parameters affecting this wear. The approach was based on the tribological triplet and material flows within the contact, using both numerical and experimental approaches. A dynamic model and valve train test bench showed that wear flows can be activated by the architecture of the valve opening system. Therefore, limiting these flows can be achieved by controlling the geometry of the system without changing the properties of the materials. In the same way, the finite element model of the local response of the seat-valve contact emphasized the influence of the "local" contact geometry. Tests carried out on the engine and on a specially adapted test bench completed the understanding of the degradation and wear mechanisms. The morphological interpretation of the worn surfaces from the point of view of material flows made it possible to understand the stages of the build-up of the protective layer.

As noted in [29], intake and exhaust valves are important engine components used to control intake and exhaust gas flow in internal combustion engines. They are used to seal the working space inside the cylinders and are opened and closed by means of a valve mechanism. These valves are loaded by spring forces and subjected to thermal stress due to high temperature and pressure inside the cylinder. The study is devoted to various types of failure of internal combustion engine valves: due to fatigue, exposure to high temperature, shock load.

Static and thermal analysis was performed on the valve (Fig. 16) by changing two materials at 5000 cycles.

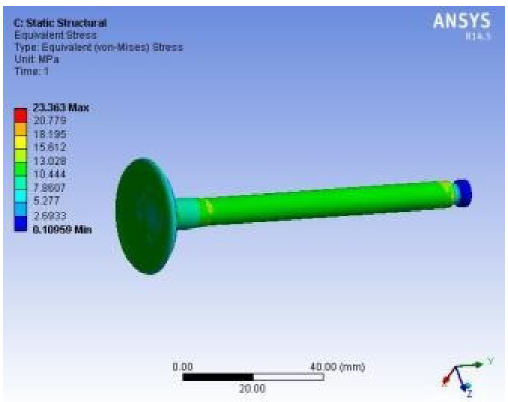

Fig. 16. Static analysis of the valve mechanism

The rapid aggravation of environmental legislation in recent decades has forced engine manufacturers to radically modify the design of parts of the gas distribution mechanism. In works [30-31] it was shown that sliding in the valve sealing area is one of the main causes of wear. Sliding wear is expected to play an even more important role in modern engines.

Experimental data obtained using a special technique on a test bench are presented. Experimental data are supplemented by FEM modeling. The simulation involves checking the sliding behavior of the valve seal area on a test bench and investigating how different parameters affect the sliding length. These parameters include combustion pressure, contact angle, contact length, valve head thickness, friction coefficient, run-in wear, and change in modulus due to temperature variations.

Conclusions

1. The valve mechanism is responsible for the coordinated operation of the engine, controlling the timely supply of fuel to the combustion chambers, the removal of spent fuel.

2. As a result of wear of the valve guide, the following valve damage and sealing problems may occur: burnt valve heads; cracks in the valve stem; cracks in the grooves for valve crackers; excessive wear of valve stem ends; worn on one side of the rocker arm; increased oil consumption due to wear of valve stem seals; worn or burnt valve seat rings.

3. The efficiency of the valve mechanism of the engine largely depends on the wear resistance of the valve guide. The problem of researching mechanisms of wear of valve mechanism parts remains very relevant due to the need for constant improvement of the design and increase in durability of internal combustion engines. In addition to the problems of valve guide wear, one of the most common problems is the study of valve seat wear, which researchers pay a lot of attention to.

4. Technological methods of surface engineering are becoming an increasingly viable alternative to structural changes made to increase the efficiency of internal combustion engines, including valve train components. To extend the service life of valves and guide bushings, a variety of modern technologies are used to increase wear resistance, restore the worn layer, and ensure reliable lubrication in various operating conditions.

5. To analyze and predict the durability of the friction nodes of the valve mechanism parts, calculated estimates of the structural characteristics of the mechanism, stress and thermal state are widely used. Numerical methods, in particular the method of finite elements, occupy a predominant place.

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Вичавка А.А. , Диха О.В. , Гетьман М.В. Аналіз трибологічних аспектів в процесі експлуатації і ремонті деталей клапанного механізму двигуна внутрішнього згорання

Проблема дослідження механізмів зношування деталей клапанного механізму залишається вельми актуальною внаслідок потреби невпинного вдосконалення конструкції і підвищення довговічності двигунів внутрішнього згорання. В роботі проведений огляд сучасних досліджень з наступних питань: аналіз умов експлуатації та несправностей клапанного механізму двигуна внутрішнього згорання, дослідження тертя та зношування деталей клапанного механізму, технології ремонту, відновлення, підвищення зносостійкості клапанів двигуна, моделювання, розрахунки деталей клапанного механізму. Показано, що важливим аспектом для аналізу зносотійкості деталей клапанного механізму є умови експлуатаціїї та характер пошкоджень поверхонь деталей пари тертя. Розглянуті існуючі гіпотези про механізми тертя, змащення та зношування деталей клапанного механізму, наведені конструкції випробувальних стендів, проаналізовані результати трибологічних випробувань. Обгрунтовано, що технологічні методи інженерії поверхні стають все більш життєздатною альтернативою конструктивним змінам для підвищення працездатності деталей клапанного механізму. Наведений огляд розрахункових методик оцінки напруженого і теплового стану деталей клапанного механізму двигунів внутрішнього згорання.

Kewwords: двигун внутрішнього згорання, клапан, напрямна, пошкодження, відновлення, зносостійкість, моделювання, метод скінчених елементів

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Establishing optimal parameters for resistance welding of agricultural machinery shafts

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Abstract

This paper searches for optimal values of resistance welding parameters of composite wires to increase the durability of agricultural machinery shafts. The optimization parameter was chosen to be the adhesion strength of the composite coating to the base of the part. The adhesion of the composite coating to the base material was evaluated using the normal tear method. To determine the optimal modes of applying composite coatings, an active experiment was conducted using mathematical planning methods. The obtained response surfaces and graphs of equal yield lines made it possible to establish the influence level of the research factors on the optimization parameter. To analyze the influence of factors on the optimization criterion, scatter graphs with histograms were constructed, which allows to graphically determine the rational values of the selected optimization criterion – the adhesion strength of the composite coating to the base during resistance welding of composite wires. The implementation of the central composite plan 2^{5-2} made it possible to establish the influence of the resistance welding parameters of composite wires (welding current strength; pressure on the electrodes; duration of the current pulse and pause; linear speed of the part rotation) on the adhesion strength of composite coatings to the base and determine their rational values.

Key words: resistance welding, composite coating, adhesion strength, agricultural machine shafts, optimal parameters.

Introduction

The technical condition of agricultural machines largely depends on the technical condition of their friction units. But today, there are still friction units of agricultural machines that are not sufficiently adapted to real operating conditions. This is evidenced by the fact that the service life of, for example, shafts is significantly lower than the service life of the machine as a whole [1]. Therefore, to increase the service life of agricultural machinery, it is advisable to increase the durability of shafts. One of the ways to solve this problem is to use technological methods to increase the wear resistance of parts [2]. Paper [3] proved the feasibility and effectiveness of using resistance welding when applying composite ceramic-metal coatings to the working surface of agricultural machinery shafts operating under abrasive wear.

For the restoration of cylindrical surfaces, various methods of surfacing, gas-flame and plasma spraying, electrolytic deposition, and resistance welding are mainly used [4]. Wide opportunities for increasing the durability of parts are opened up by the use of resistance welding and powder brazing, which has the following undeniable advantages [5]: high productivity; minimal losses of filler material (during welding and subsequent processing, losses do not exceed 5%); practically no burnout of chemical elements of the filler material; insignificant thermal effect on the part (the zone of thermal influence does not exceed 0.3 mm); the ability to apply a thin, dense, pore- and shell-free layer of metal with high hardness and with minimal allowance for machining.

Literature review

Resistance welding is carried out on special installations by joint deformation of the welding material and the surface layer of the base metal, heated at the place of deformation to a plastic state by short (0.02...0.5 s) current pulses of 5...30 kA [6]. Depending on the type and shape of the filler material, there are resistance welding of compact (tape, wire), powder (granular), and combined materials.

In order to achieve high wear resistance of the restored shafts, coatings that work well under abrasive wear conditions are needed. In this case, preference should be given to composite coatings [7]. Studies [8] state that the method of resistance welding using composite wire has wide technological capabilities and provides obtaining composite coatings with the achievement of the required performance properties of parts.

One of the main operational properties that determine the durability of parts with composite coatings, applied by resistance welding of composite wire in particular, is their adhesion strength to the base metal, which in turn depends on the modes of forming the composite coating.

From this point of view, it is quite reasonable to study the effect of resistance welding parameters on the adhesion strength of the composite coating with the base.

Paper [9] presents a methodology for optimizing technologies for coating application according to the strength and wear resistance criteria, which ensure the maximum possible strength and durability of the part with a coating at minimal cost for the coating application process. The prospects of using the optimization direction by the method of experiment factorial planning have been convincingly proven on such technologies as gas-flame and detonation spraying [10], vacuum plasma spraying [11], electric spark alloying [12], ionic nitriding [13], and finishing antifriction non-abrasive treatment [14, 15].

Purpose

The purpose of the presented research is to establish rational values for the parameters of resistance welding of composite coatings in order to increase the strength of their adhesion to the base.

Research Methodology

In most cases, the performance of agricultural machinery parts restored by resistance welding is determined by the adhesion strength of the applied coating to the base. Therefore, this indicator should be chosen as the optimization criterion. It should be noted that the adhesion strength of composite coatings to the base largely depends on the modes of resistance welding.

Experimental studies of the resistance welding of composite wires were carried out on the installation 011-1-02N. The following main parameters were monitored in the process of resistance welding of composite coatings: applied pressure value; electric current strength, current pulse duration and pause between pulses; part rotation speed and welding head feed rate.

The most technologically advanced materials for resistance welding of composite coatings are composite wires, which represent a sheath filled with the necessary components in the form of a powder. In the course of the study, the sheath material used was steel 08 ps, the chemical composition of which is shown in Table 1.

Table 1

Chemical composition of steel 08 ps, % [16]

Brand	Fe	C	Mn	Si	Cr	S	P	Cu	N	As
					no more than					
Steel 08ps	Base	0.05-0.11	0.35-0.65	0.05-0.17	0.10	0.04	0.035	0.25	0.25	0.08

The main material of the matrix is iron – PZhV-5 powder (Table 2), an inexpensive material with high welding properties.

Table 2

Chemical composition of iron powder PZhV-5, % [16]

Brand	Fe	C	Si	Mn	S	P	O	Residue insoluble in HCl
PZhV 5	Base	0,25	0,30	0,50	0,05	0,05	2,0	0,6
C	Si	Mn	Ni	S	P	Cr	Cu	Fe
0.27 - 0.34	0.9 - 1.2	1.0 - 1.3	1.4 - 1.8	≥ 0.025	≥ 0.025	0.9 - 1.2	≥ 0.3	~94

Composite powders were used in the core of the welded flux-cored wires: nickel-clad ceramics, which improves the thermal and electrophysical characteristics of the composite coating. Chromium carbide was used as filler.

Thus, a wire with a diameter of 2 mm was made for the study, the microstructure of which is shown in Fig. 1.

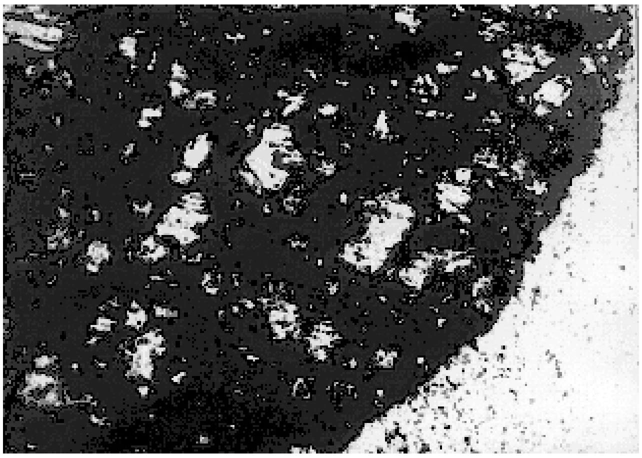


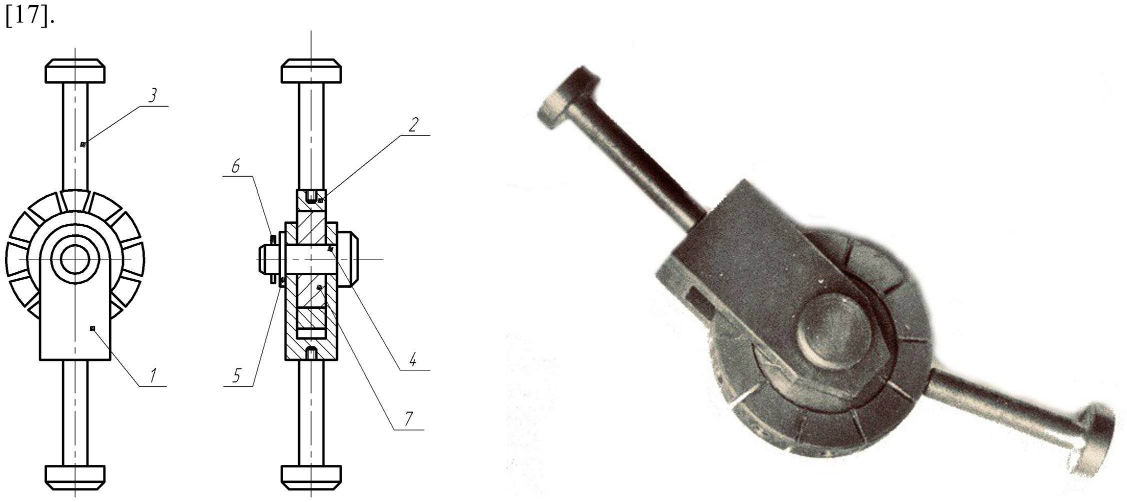
Fig. 1. Microstructure of flux-cored wire, ×100 % [16]

The resistance welding of composite wires of the specified composition was carried out on samples made of steel 50, which is widely used for the manufacture of agricultural machinery shafts.

To determine the optimal modes of composite coatings application, an active experiment was conducted using mathematical planning methods.

Since the optimization parameter is the adhesion strength of the composite coating to the base, the choice of the methodology for its evaluation deserves special attention.

The evaluation of the composite coating adhesion to the base material was carried out by the normal tear method using a special device developed by the authors, the scheme and general view of which are shown in Fig. 2 [17].



a) b)

Fig. 2. Scheme (a) and general view (b) of a device for determining the adhesion strength of a composite coating to a base metal: 1 – fork; 2 – split bushing; 3 – clamps; 4 – axis; 5 – washer; 6 – cotter pin; 7 – sample [17]

In accordance with the proposed methodology [17], a bushing 2 (Fig. 2), previously cut into sectors, each with threaded holes for screwing the clamp 3, was glued to the outer surface of the sample 7, which was studied with a composite coating. After polymerization of the glue, the cuts made on the bushing were deepened to the surface of the base metal. The sample with the glued sectors was mounted on the axis in the fork 1 of the device. The clamps were screwed into the threaded holes of the fork and the sector to be torn off. The sectors were torn off using a tensile machine MP-500, and the adhesive stress was calculated using the formula:

$$\sigma_{ad} = \frac{P}{F},$$

where P – tearing force, N; F – area of the sector inner surface, m^2.

To determine the optimal modes of composite coatings application, an active experiment was conducted using mathematical planning methods.

The purpose of the experiment series was to implement the central composite plan 2^{5-2}, which resulted in the determination of a number of factors influence (welding current; electrode pressure; current pulse duration; pause duration; linear rotation speed of the part) on the adhesion strength of composite coatings to the base.

The rotational plan has five levels: top, zero, bottom, and two outer levels ("star points"). The interval from the zero level to the "star points" is defined by the "star shoulder" equal to 1.68 [18]. In order to prevent the influence of systematic errors caused by unconsidered factors, the experiments were conducted in a random order, for which a table of random numbers was used.

The experimental data were processed using the STATISTICA 12.0 software package.

Results

The resulting regression equation is as follows:

$$Y = 144,983 + 22,066x_1 + 16.693x_2 + 18.193x_3 - 3.14x_4 - 0.779x_5 - -25.563x_1^2 -$$
$$-7,127x_2^2 - 2,327x_3^2 - 2,615x_4^2 - 2.065x_5^2 + +7.023x_1x_2 + 4.948x_1x_3 - 11.04x_1x_4 + 10.319x_1x_5 -$$
$$-0,652x_2x_3 - 5,715x_2x_4 + 9.544x_2x_4 + 2.91x_3x_4 - 0.68x_3x_5 + 9.057x_4x_5$$

where x_1 – welding current strength, kA;
x_2 – pressure on the electrodes, MPa;
x_3 – duration of the current pulse, s;
x_4 – pause duration, s;
x_5 – linear speed of part rotation, m/s.

The statistical evaluation of the obtained results allows considering the experiments to be equally accurate. The significance of the obtained coefficients was checked using the Student's criterion, and the adequacy of the equations – using the Fisher's criterion.

The analysis of the Pareto Chart (Fig. 3) and the tabular results of the experiment revealed that the following factors have the greatest influence on the adhesion strength: x_1, x_3, x_2 and the quadratic function of x_1 and x_2.

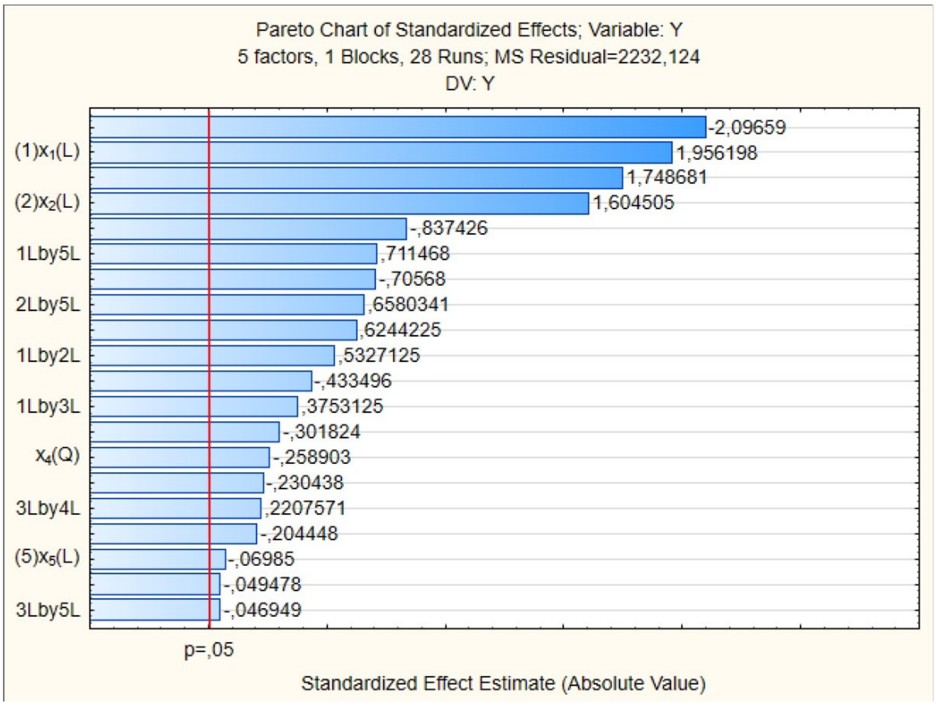


Fig. 3. Standardized Pareto Chart for adhesion strength

The response surfaces and graphs of equal yield lines (Fig. 4) make it possible to note that the highest adhesion strength of composite coatings to the base occurs at the following values of the factors: x_1 = 14.8…15.2 kA; x_2 = 0.3…0.4 MPa; x_3 = 0.06…0.08 s; x_4 = 0.05…0.06 s; x_5 = 0.018…0.02 m/s.

To analyze the influence of the factor on the optimization criteria, we constructed experimental scatter graphs with histograms (Fig. 5), which allows to graphically determining the rational values of the selected optimization criterion – the adhesion strength of the composite coating to the base during resistance welding of composite wires.

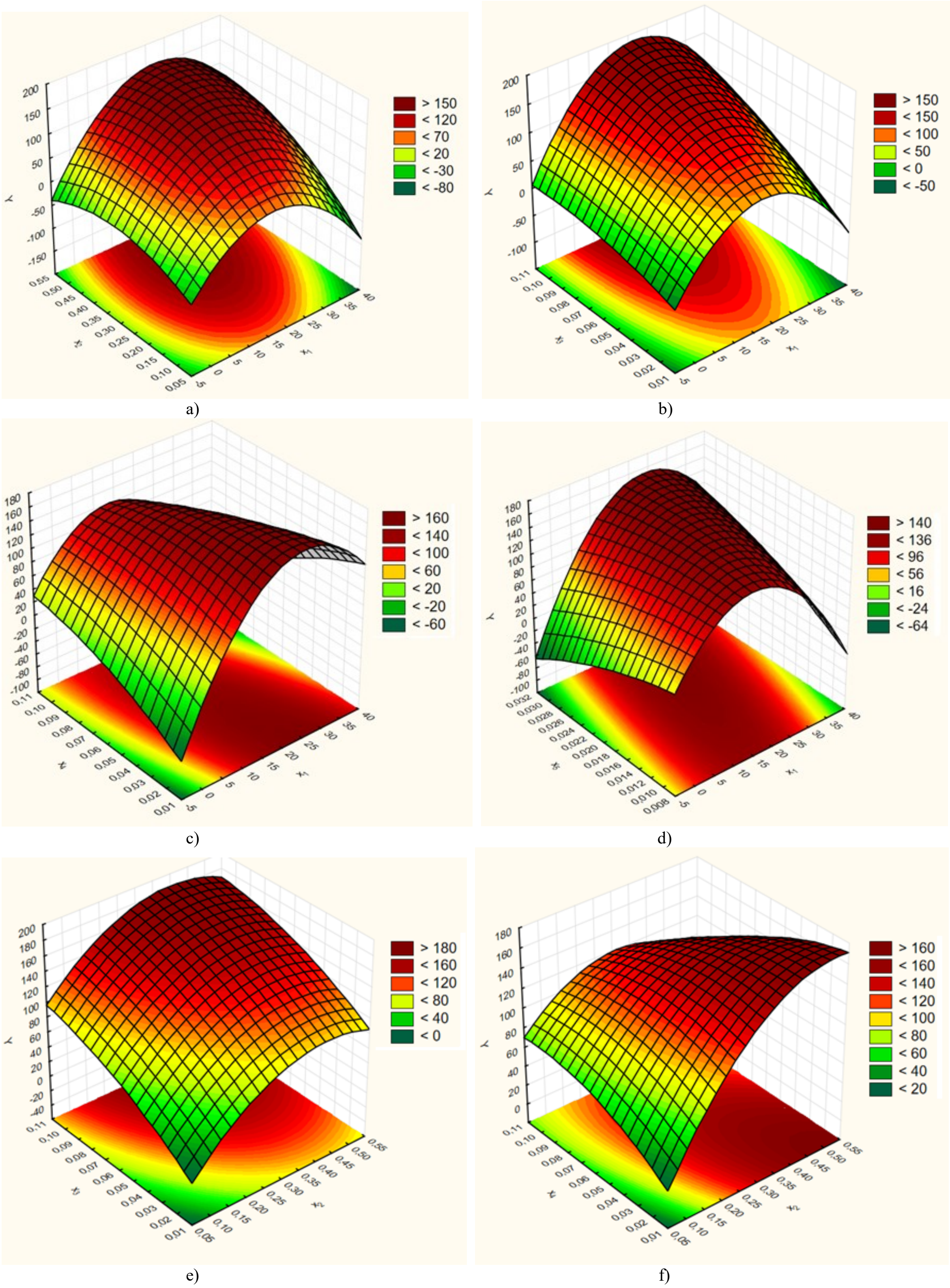


Fig. 4. Response surfaces and graphs of equal yield lines *Y*: a – *Y* (x_1, x_2), b – *Y* (x_1, x_3), c – *Y* (x_1, x_4), d – *Y* (x_1, x_5), e – *Y* (x_2, x_3), f – *Y* (x_2, x_4)

Analysis of the response surfaces and graphs of equal yield lines for the selected optimization criterion (Fig. 4), as well as scatter graphs of the technological factors influence (Fig. 5), allows to determine their rational values: x_1 = 15.179 kA; x_2 = 0.3 MPa; x_3 = 0.06 s; x_4 = 0.06 s; x_5 = 0.01964 m/s. Taking into account the technological capabilities of the installation for resistance welding of composite wires when machining shafts ∅ 50 mm, the following values should be considered rational modes: welding current I = 15 kA; electrode pressure P = 0.3 MPa; current pulse duration τ = 0.06 s; pause duration τ_1 = 0.06 s; linear speed of part rotation V = 7.5 rpm.

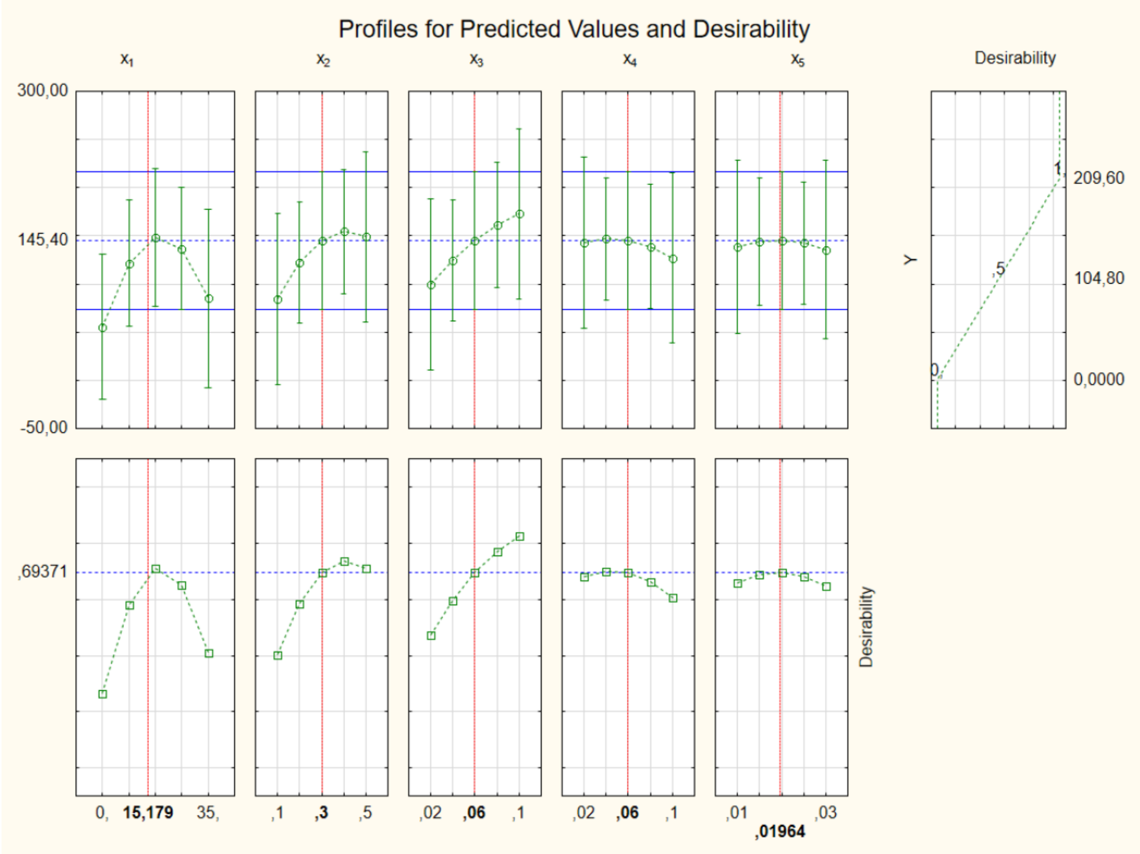


Fig. 5. Scatter graphs with histograms characterizing the influence of the studied factors on the adhesion strength of the composite coating to the base during resistance welding of composite wires

Conclusions

1. Given that the service life of agricultural machine shafts is significantly shorter than the service life of the machine as a whole, the issue of increasing the parts durability is particularly important.

2. The use of resistance welding technology of composite wires opens up great opportunities to improve durability.

3. Since the adhesion strength to the base is one of the main operational properties of parts that determine their durability, this parameter must be improved by selecting rational values for the resistance welding modes of composite wires.

4. To determine the optimal modes of applying composite coatings by resistance welding, an active experiment was performed using mathematical planning methods. The analysis of response surfaces and graphs of equal yield lines for the selected optimization criterion made it possible to establish rational values of the resistance welding modes. Taking into account the technological capabilities of the installation for resistance welding of composite wires, it is recommended to process shafts ∅ 50 mm at the following values: welding current I = 15 kA; electrode pressure P = 0.3 MPa; current pulse duration τ = 0.06 s; pause duration τ_I = 0.06 s; linear speed of part rotation V = 7.5 rpm.

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Черновол М.І., Шепеленко І.В., Василенко І.Ф., Лещенко С.М., Красота М.В., Артюхов А.М.
Встановлення оптимальних параметрів контактного наварювання валів сільськогосподарських машин

В роботі виконано пошук оптимальних значень параметрів контактного наварювання композиційних дротів задля підвищення довговічності валів сільськогосподарських машин. За параметр оптимізації обрано міцність зчеплення композиційного покриття з основою деталі. Оцінку зчеплення композиційного покриття з матеріалом основи здійснювали методом нормального відриву. Для визначення оптимальних режимів нанесення композиційних покриттів проводився активний експеримент з використанням методів математичного планування. Отримані поверхні відгуку та графіки ліній рівного виходу дозволили встановити рівень впливу досліджуваних факторів на параметр оптимізації. Для аналізу впливу факторів на критерій оптимізації побудовані графіки розсіювання з гістограмами, які дозволяють графічно визначити раціональні значення обраного критерію оптимізації – міцності зчеплення композиційного покриття з основою при контактному наварюванні композиційних дротів. Реалізація центрального композиційного плану 2^{5-2} дозволила встановити вплив параметрів контактного наварювання композиційних дротів (сили зварювального струму; тиску на електродах; тривалості імпульсу струму та паузи; лінійної швидкості обертання деталі) на міцність зчеплення композиційних покрить з основою та визначити їх раціональні значення.

Ключові слова: контактне наварювання, композиційне покриття, міцність зчеплення, вали сільськогосподарських машин, оптимальні параметри

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Restoration and wear resistance of electric transport sliding contacts

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Abstract

The electrical contact insert of the current-carrying suspension of the electric vehicle belongs to the fast-wearing elements that require frequent replacement and attention to ensure standard performance. The purpose of this study was to develop a technology for manufacturing graphite-filled electrical contact inserts from waste materials and by modifying the composition of the composite. As a result of difficult operating conditions, coal current collector inserts of electric transport are subject to considerable wear. The causes of increased wear are electrocorrosion in contact with the conductor under current, abrasive wear from sliding on the wire with increased dustiness and air humidity. The technological process of manufacturing graphite current-collecting inserts from used graphite components is proposed. To prove the functionality of the restored current-collecting inserts, the strength, electrical conductivity and tribological characteristics of the material were tested. The results of experimental tests showed a slight decrease in material hardness and an increase in electrical resistance within acceptable limits. Bench wear tests showed improved tribological properties of the restorative insert material with the addition of copper powder.

Keywords: electric transport, current collector, contact insert, graphite, recovery, sintering, wear resistance, electrical resistance

Introduction

Electric transport is an integral part of the unified transport system of many cities of Ukraine. Reliability and efficiency of the current collection system and current collector parts of the trolleybus is one of the important problems of operation of electric transport [1-10[. During operation, there is an intensive operation of the current collector head of the trolleybus, and a deterioration of the current collection process, which is affected by the state of the contact network, the quality of the used lubricants, and the operating conditions. The reliability of the contact "current receiver of electric rolling stock - contact suspension" is primarily determined by its service life and reliability during operation and depends on the state of operation of the interacting elements: the head of the current receiver and the contact wire. The wear resistance of the contact significantly depends on the physico-mechanical, electrical and tribotechnical properties of the materials of its interacting elements. In order to improve these characteristics, it is necessary to apply effective methods and technologies of manufacturing, strengthening or modification of the conjugated contact elements of the current collector.

The most responsible part of the current collector is the contact head (Fig. 1). It should provide stable current collection during movement at high speeds, on curves, as well as when the trolleybus deviates from the axis of the contact wire suspension.

The end of the rod of the current collector covers the insulating sleeve 2 (Fig. 1), on which the steel holder 1 is fixed with bolts. A spherical axis is installed in it in the upper part. On the axis is the rotating part of the contact head, which consists of a holder, a copper insert 3, two cheeks 5 and a replaceable, carbon insert 6. The upper part of the axis is located between the holder and the insert, which are rigidly connected by two screws. The presence of spherical surfaces of connected parts enables the variable insert to rotate around a vertical axis.

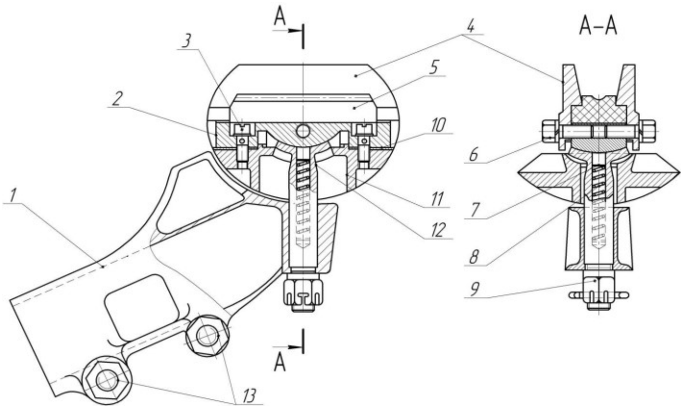

Fig. 1. Contact head of the current collector: 1, 11 – holders; 2 – insert; 3, 6, 13 – bolts; 4 – cheek; 5 – carbon insert; 7 – brush; 8 – spring; 9 – nut; 10 – gasket; 12 – the fifth.

The spherical surfaces of the contact head must be lubricated with a thin layer of grease (AeroShell Grease 7). To reduce the transition resistance between the insert and the holder, a copper graphite brush 8 with a spring is installed, which creates the necessary pressure of the brush on the insert. The insert is installed on the liner and fixed with bronze cheeks, which simultaneously act as guide ribs when the head moves along the contact wire. Cheeks are pressed to the insert with bolts 7. To prevent the contact head from falling to the ground when coming off the rod, a protective tape 16 is provided.

The weakest element of the current collector is the contact insert, which slides along the copper trolleys of the power supply. In fig. 2 presents various types of trolley bus inserts.

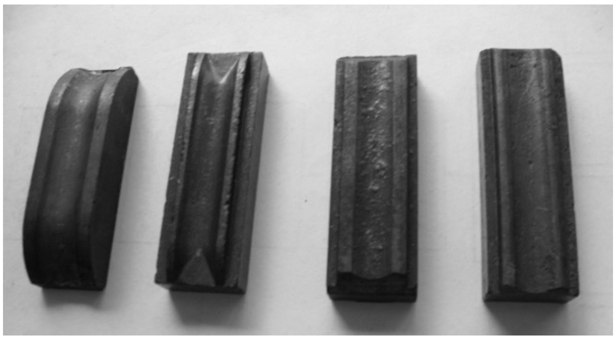

Fig. 2. Types of trolleybus inserts

As a result of friction and the formation of spark discharges, the inserts are subject to intense wear. Their regulatory term provides80 km. mileage Inserts also often fail due to mechanical damage. The operational characteristics of the inserts are presented in Table 1.

Table 1

Operating characteristics of inserts when working together with MF-100 copper wire

Indicator	State of sliding contact		
	Dry	Wet	Wet
Linear wire wear, μm/10,000 passes	0.00	0.20...0.25	0.25...0.30
Wire wear area in cross-section, mm2/10,000 passes	0.00	0.003...0.004	0.004...0.005
Coefficient of friction	0.13	0.05...0.06	
The decline of insult in contact, V	0.40...0.60	0.25...0.40	
Linear wear of inserts, mm/100 km of mileage	0.1...0.2	0.2...0.4	0.04...0.06

According to the technical conditions, the current collector removes a constant voltage of 550 V, while the permissible current should not exceed 170 A. The pressure of the current collector on the contact wire is up to 140 N. The contact insert is a part of the current collector head, which directly contacts the wire and carries out current collection. The quality of current collection largely depends on the insert: continuity of contact, amount of mechanical and electrical wear of the contact wire, sparks, radio interference, electrical losses.

The most common types of wear of the tribosystem "contact wire - insert" are abrasive, fatigue, oxidative and molecular-mechanical wear. Several types of wear may appear simultaneously, but one of them will always be dominant. Abrasive wear occurs as a result of products of wear and external dust falling into the friction plane, as well as in the presence of solid inclusions that form the basis of the material of the conjugated elements of the tribosystem. Most often, microchips, small particles torn from the friction surface, appear on graphite inserts, but at the same time the surface retains its polish. Characteristic wear damage of coal inserts in operation are shown in fig. 3.

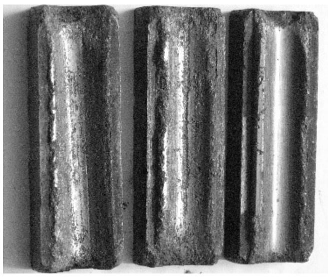

Fig. 3. Wear damage of coal inserts

In case of poor adjustment of the contact suspension, carbon inserts are characterized by damage and excessive activation or lateral wear. Chips occur only when the adjustment of the contact suspension elements is disturbed, cracks occur due to impacts on the insert and under conditions of impaired current collection, fires occur. Fatigue wear is associated with volumetric deformation of the friction surfaces and cracking of the over-riveted metal layer, followed by its removal. Oxidative wear is associated with the formation and destruction of thin oxide films on friction surfaces. Mechanical wear occurs as a result of the friction process and as a result of shocks of the current collector insert against the contact wire and depends on the characteristics of the contacting materials, the state of their surfaces, the pressure at the contact point, the sliding speed and the uneven height of the wire suspension.

Tribotechnical materials and technologies of sliding electrical contacts (inserts)

Graphite is the main material used in friction pairs operating in a sliding contact system, as it acts as a dry lubricant. Contacts of this type are a kind of friction pair in which the contacting elements slide one after the other without breaking the electrical connection. Therefore, along with the above-mentioned requirements, the contact material must also possess a complex of antifriction properties in relation to dry friction conditions, and the contact pair cannot consist of the same materials, because otherwise friction surfaces will seize even under normal operating conditions, not to mention about working in a vacuum. The hardness of the materials that make up the contact pair must be different. It is desirable that the counter-body (current-carrying element) is more solid (approximately 1.3-2 times) than the moving contact (current-collecting element), then the service life of the contact pair increases, and replacing the current collector is usually easier than other elements of the electrical circuit . The required hardness ratio is achieved by adding solid lubricants (molybdenum disulfide, zinc sulfide, selenides of some liquid metals, calcium fluoride, graphite, etc.) or low-melting metals (for example, gallium) to the corresponding contact material, which become liquid during the operation of the contact pair.

In this case, areas of solid lubrication perform anti-friction functions, and a metal base with low electrical resistance provides the main electrical connection in the connected contact node; in the presence of a low-melting metal in the material, together with the basis of the power transmission, wear is reduced due to the replacement of dry friction with liquid friction when the additive is melted. In the process of operation, when the contact surfaces are moved relative to each other, both the actual physical contact surface changes (frictional surfaces act unevenly) and the actual electrical contact surface (not the entire contact surface participates in electrical transmission due to roughness and the presence of non-conductive or low-conductivity phases on it) . In the process of commutation of an electric current, the wear of the contact surfaces of the friction pair, depending on the quality and material of the contacts, increases 10-100 times compared to the wear in the de-energized state: electric spark and arc processes destroy the friction surface, contributing to its mechanical wear, and heating also accelerates the interaction material with the surrounding external environment, causing a loss of their strength and hardness.

Sliding contacts are used in the form of plates, rods, cylinders, darts, etc. in electric motors, dynamos, potentiometers, current collectors, switches and other devices. The basis of the contact material is copper or silver, and graphite is most often used as a solid lubricant. Copper-graphite contacts contain 8-75% graphite, have good electrophysical properties, are cheap and work reliably in difficult operating conditions (brushes of electric motors and dynamos, magnetos, etc.). Bronze-graphite contacts contain 2-5% graphite, 70-80% copper, ost. - tin, iron, nickel. Such contacts are used as collector plates of pantographs for powering the motors of electric trains at speeds up to 1500 m/min and under the influence of relatively high pressures and shocks, and the current-carrying wire wears out minimally.

Silver-graphite contacts contain 2-50% graphite and work in precision measuring devices either dry or completely immersed in lubricant at speeds up to 20 m/min and a load of 0.05-0.07 MPa.

Silver-based sliding contacts are prepared from a mixture of powders of the corresponding components (for PDS-70 material, silver-palladium alloy powder is used, and for SNDSM-2.5 material, silver-palladium-nickel alloy powder is used). Large-sized blanks are pressed, sintered in the solid phase, pressed, annealed, extruded into a wire rod or tape (rolling and drawing are also possible) and contacts are stamped or planted. Contacts of the Sndsm-7.5 brand are pressed immediately from a mixture of powdered silver, nickel and molybdenum disulfide, solid-phase sintering of the blanks is carried out in argon, and then pressed and annealed. The same is done in the case of obtaining silver-graphite contacts.

When manufacturing copper-graphite electric brushes, which also include lead or tin additives, it is necessary to create a copper frame that gives the material maximum electrical conductivity. Technologically, this problem is solved in several ways. According to one of them, porous graphite is impregnated with molten copper, which turned out to be economically beneficial when the copper content in the composition is more than 50% (by mass). Porous graphite should have a through porosity of 20-35% and be strong. Impregnation with copper is carried out under pressure.

The most common method is the pressing and sintering of a mixture of copper powder with various carbon materials. Many companies make copper graphite brushes from mixtures of copper powders and natural graphite, but most of the brushes contain, in addition to graphite, other carbon components that are introduced to increase strength, improve wear resistance and reduce contact resistance. Such additives are pitch (increases strength and improves pressing of the mixture), or carbon black-coke fines (increases wear resistance), rubber (increases strength). When using a binder and other additives, an important role is played by the operation of mixing the initial powders, because in the final product the copper component should cover the particles of the carbon component as best as possible. As a rule, carbon components such as graphite, carbon black and pitch are mixed first. For this, heated mixers are used. After cooling, the mixture is ground into powder, the fines are sifted out and mixed with copper powder. The resulting charge is pressed (200-400 MPa) into a product or blank. Sintering is carried out at 700-800 ºC in continuous furnaces with a protective atmosphere. If the blanks contain connecting components, then sintering is reduced to coking the pitch with the formation of a strong coke backbone, in the pores of which particles of metal powders are held. After sintering, the blocks are cut into individual brushes, and the individually sintered brushes are machined and reinforced with conductive elements.

You can make electric brushes from graphite coated with copper or its alloys. In this case, graphite, zinc and lead powders are immersed in aqueous solutions of CuSO4 or CuCl4. At the same time, copper is deposited on the graphite surface, and part of the lead is mechanically captured. The best wear resistance, hardness and strength are achieved with a lead content of 1-2%. Such powders are sintered at 400 ºC, that is, 250 ºC lower than ordinary mixtures of copper, graphite and lead powders. The structure of the products is mesh, which provides them with high wear resistance and good electrical, thermal and mechanical properties.

Research on the reliability and wear resistance of working parts of sliding electrical contacts, especially electrical brushes, is carried out in three main directions:

- improvement of the structure of the material and the design of the working element;
- optimization of the choice of constituent and granulometric parameters of the composition of charge materials;
- optimization of technological modes of production of the working element.

Electric brushes based on carbon with various additives and layered brushes based on alternating layers of carbon fabrics and polymer binders with anti-friction additives do not ensure the creation of a continuous intermediate film (polish) between the collector and the brush material.

For direct current electric machines that work in a single-use mode and with high-density operating currents, in order to reduce the generation of sparks, current-collecting brushes are used, formed by sections of twists of insulated current-conducting cores from a metal wire of low electrical resistance, for example, beryllium bronze.

For electric machines, the operating conditions of which are characterized by the special tension of the current-collecting devices due to vibration and large currents, in order to increase the wear resistance of the brushes and the collector, brushes with different physical and mechanical characteristics and which are placed taking into account the polarity are recommended.

Each of the known measures of constructive implementation does not solve the problem of reducing the value of the transient resistance and the loss of current transmission capacity. It is possible to reduce and at the same time stabilize the transient resistance of sliding current collectors by additionally passing through the contact a low-frequency direct or alternating current of a high-frequency current [11].

Brushes based on crystalline graphite with anisotropy of electrical resistance, as well as brushes containing carbon fabrics, thermo-reactive binders and anti-friction components have high switching ability, wear resistance and minimal energy loss in contact.

Optimization of the composition and granulometric parameters of the composition of charge materials is the second direction of research into current-carrying sliding elements, which are carried out in order to improve their commutative properties and wear resistance.

A mixture of graphite and hardened coke, copper (introduced in the form of a coating layer on a coke particle) and binder [12], as well as a mixture of copper and graphite in the form of pressed powders, which represent a single matrix, are proposed for sliding elements of electromotive transport , and granular inclusions containing copper and molybdenum disulfide are evenly distributed in the volume of this matrix, and the copper in the granules is introduced in the form of a coating layer applied to molybdenum disulfide powder particles [13] according to the following ratio of components: copper 25 ... 33%, granules 25 ... 39%, graphite - the rest. Granules have dimensions of 80 ... 200 μm according to the following ratio of components in the body of the granule: copper 20 ... 31%, molybdenum disulfide - the rest. Granular inclusions strengthen the matrix and increase wear resistance. Copper-graphite and copper-copper interparticle contacts cause high electrical conductivity. To manufacture the sliding element, artificial graphite powder with a dispersion of 40 ... 200 µm was mixed with copper powder 40 ... 150 µm and molybdenum disulfide powder 150 ... 300 µm, on which a layer of electrolytic copper was applied. The resulting pressed powder was pressed and then sintered.

The composition of the carbon-containing material [14] includes a mixture of natural and artificial graphite, and copper is introduced in the form of a coating layer applied to the particles of natural graphite, which wets this graphite by spontaneously spreading over it. The ratio of components in the press powder is: natural graphite 50.0 ... 75.0%, artificial graphite 7.0 ... 35.0%, copper 5.0 ... 25%, binder - the rest. Natural graphite is the most inert carbon material to oxidation when heated and has the best self-lubricating properties. Due to the modification of natural graphite with niobium, copper enters into physical and chemical interaction, moistens and increases its electrical conductivity. At high currents, the sliding element heats up and electroerosion of graphite occurs, but the copper does not peel off from it. Powders of artificial graphite (40 ... 200 µm), copper (40 ... 150 µm), natural graphite (50 ... 200 µm) with a modifier and binder powder are mixed, pressed and sintered.

According to another method [15], pressing is carried out at a pressure of 5 ... 30 MPa at a temperature of 165 ... 210 °C, and heat treatment is performed at a temperature of 220 ... 600^0C. The content of a thermosetting binder, for example, phenol-formaldehyde resin, is 7...50%, metal materials, for example, copper - 0...70%, and carbon graphite materials, for example, natural and artificial graphite, carbon black, carbon fibers - 20 ...93%. The composition may also include known alloying, polishing, anti-friction, plasticizing and polymerization-accelerating binder additives. The method of manufacturing a current-carrying sliding element [16] from copper-plated graphite powder, on the surface of whose particles a protective layer of tin is applied, and an organic binder, is distinguished by the fact that a layer of copper and a layer of graphite are applied one after the other, along or across this element at an angle of 0 ... 90o to the working surface with the following ratio of components in the material: copper - 5 ... 48%; graphite - the rest. The layers are formed in the form of hollow cylinders inside each other, along this element or in the form of a combination of cylinder segments formed one on top of the other along or across this element. High hardness, strength and wear resistance, the highest electrical conductivity and good interparticle contacts between copper and graphite are ensured when copper is applied in layers on graphite. The pressed powder is applied in functional layers, pressed and sintered.

According to another [17] method, a mixture of graphite-containing material with a crushed binder is ground to particle sizes of 0.040 ... 0.071 mm and mixed with graphite-containing material powder with a fraction of 0.2 ... 1.0 mm, and heat treatment is carried out simultaneously with the pressing process with exposure under pressure Graphite electrode waste with an ash content of less than 0.5% is used as a graphite-containing material, and phenol-formaldehyde resin is used as a binder. When the graphite-containing material and resin are simultaneously crushed, a homogeneous powder-like mixture is obtained, in which the finely dispersed particles of the binder are evenly distributed in the volume of the finely dispersed graphitized material. After thorough mixing of the obtained mixture with the powder of graphitized material with a fraction of 0.2...1.0 mm, a composition is obtained in which, when pressed, finely dispersed particles fill the voids between coarsely dispersed particles, forming a uniform dense packing. Under the simultaneous action of pressure and temperature, the binder, melting and enveloping the particles of the graphitized material, penetrates into the pores, squeezing out air, and the particles of different fractions, clinging to each other and being incorporated into each other, form a homogeneous structure of the product with minimal porosity. Temperature exposure contributes to a more complete flow of these processes and their completion as a result of polymerization of the binder over the entire thickness of the product. The dense, uniform structure provides stable, low electrical resistance due to the increase in the contact surface between the particles, ensures good sliding of the moving collector on the stationary brush, and reduces sparking.

Technology of restoration of current collector inserts

The analysis of the defects of the inserts of the current collectors of the trolleybus showed that it is possible to restore its operability by restoring the surfaces under the contact wire. The technological operations of restoration are shown in Table 2. The amount of material of the worn insert, which is thrown into the scrap, is 35% of the total weight of the new coal insert. Therefore, it is rational to use the worn-out part of the carbon insert in the subsequent production of new carbon inserts of the current collector of the trolley bus.

Table 2

The technological process of restoring the current collector insert

The name of the operation	Performing the operation
Defective	Suitability of the insert for further operation
Grinding	Grinding of spent inserts of current collectors
Screening	Sifting of components of spent inserts
Preparatory	Preparation of the mixture
Pressing	Pressing new inserts
Heat treatment	Hardening of pressed inserts
Control	Product quality control

At the next stage, the selection of equipment and tools was carried out as the basis of the rationality and economy of the process of restoration of parts. In the conditions of repair enterprises, universal equipment is beneficial, which allows you to perform a large number of operations. Based on the conditions of the technological process and economy, we choose the equipment, cutting and measuring tools, with the help of which it is possible to perform all the necessary operations.

The technology involves the grinding of activated inserts of trolleybuses with the help of a rotary crusher (Fig. 4). Grinding is carried out in the crusher thanks to the rotor, on which the knives are fixed, which break the pieces of graphite against the baffle plates fixed in the housing. The elements of the inserts also break against each other after gaining acceleration from the rotor. Grinding is carried out until the powder cannot enter the lower chamber through the installed grate. The body is lined from the inside with wear-resistant metal. In the future, it is necessary to divide the obtained powder into fractions. It is proposed to do this with the help of a separator, which separates the graphite powder into two fractions: small and large. The principle of operation is based on the passage of a shallow fraction through a profiled disk under the action of air pressure and centrifugal force. Powder supply is carried out through one nozzle together with air. The rotor rotates and gives centrifugal force to the small fraction, due to this, it passes through the profiled disk and enters the outlet of the fine powder, while the large fraction remains at the bottom of the case.

The next technological operation is the mixing of components. Mixing is done in mixing drums. Additionally, PMS-1 copper powder (220μm) in the amount of 5% is added to the obtained graphite material.

The finished mixture is sifted and pressed in molds (200-400 MPa).Inserts are pressed on a hydraulic press. For the production of inserts, the mold shown in fig. was designed and manufactured. 5.

Fig. 4. Crushing of graphite inserts

Fig. 5. General view of the mold for graphite inserts

Sintering of experimental samples and full-scale inserts was carried out in a vacuum electric furnace at a temperature of 180...220ºC.

Samples of the obtained experimental compositions (Fig. 6) were examined for hardness and electrical conductivity.

Fig. 6. Research samples

The hardness of experimental and serial samples was measured by the Rockwell method on the TK-2 device on the B scale, provided there was no working load. The average results of hardness measurements are shown in Table 3.

Table 3

HRB hardness of experimental and serial samples

Sample	1	2	3	4	Serial sample
HRB	80	79.5	76.5	66.5	84

The obtained results show that the conventional hardness of experimental and serial samples differs slightly.

The electrical resistance of experimental and serial samples was measured with an ohmmeter with an accuracy of 0.05 Ohm. The specific resistance was calculated according to the formula:

$$\rho = \frac{RS}{l},$$

where R is the resistance determined by an ohmmeter, Ohm;
S is the cross-sectional area of the sample, mm^2;
l is the sample length, mm.

The results of determining the electrical resistance are shown in Table 4.

Table 4

Electrical resistance of experimental and serial samples

Sample	R, Ohm	ρ	*l*	S
1	1.4	7.02	25.5	128.2
2	1,2	6.41	23.7	126.6
3	1.1	5.84	23.8	126.4
4	1.0	5.36	23.6	126.6
Serial sample	1.1	6.07	23.0	127.0

The resistance of the serial samples is approximately 25% lower than the resistance of the experimental materials, which requires certain optimization of the chemical and granulometric composition and technologies of manufacturing inserts.

Results of tests on the wear of electrical contact inserts

Tests were carried out on a laboratory bench to check the functionality of restored copper-graphite inserts (Fig. 7).

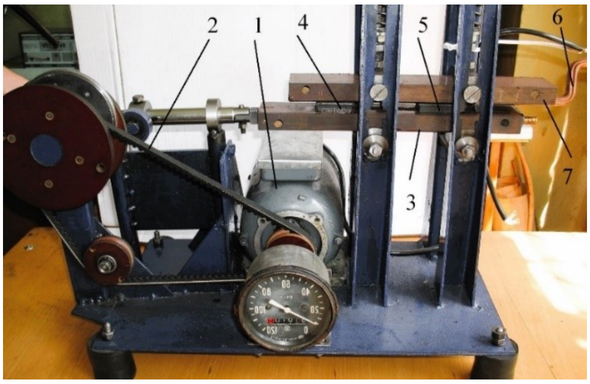

Fig. 7. Stand for testing trolley bus pantograph inserts: 1-electric motor, belt drive, 3-moving support, 4-test sample 1, 5-test sample 2, 6-pin wire, 7-wire clamp.

The test bench simulates the sliding contact of a natural graphite insert of a current collector with a current-conducting wire. Electric motor 1 serves as the drive for the reciprocating movement of the insert samples. The rotational movement is transmitted to the crank mechanism through the belt system 2. As a result, the support with the samples placed on it receives a reciprocating movement. Experimental 4 and serial 5 samples of the current collector insert are fixed on the support 3. The contact wire 6 is fixed in the upper clamp 7. The clamp 7 with the wire is pressed against the insert samples with the help of springs with a given force. In this way, a sliding mechanical contact is created between the insert and the wire. The amount of wear was determined by periodic measurement of the linear dimensions of the inserts. The results of wear determination are shown in the graph of fig. 8.

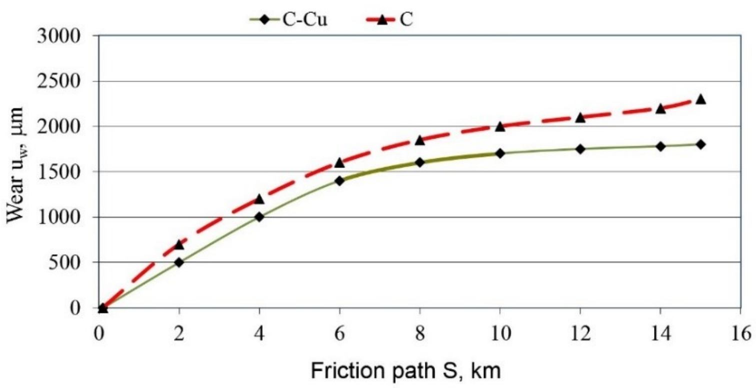

Fig. 8. Dependence of wear of the insert on the friction path

The change in the thickness of the insert in the center of the radial recess was taken as the wear criterion. The maximum wear of the insert was 2.5 mm on average for 15 km of the friction path. The insert restored without the addition of graphite powder and with the addition of 5% Cu powder was compared. From the results of wear tests, it can be seen that the insert with the addition of copper has an average of 10% less wear, which indicates the effectiveness of the proposed technology. Along with this, it should be noted that the wear resistance of restored inserts is 30% lower compared to new serial inserts (average literature data on the wear of serial inserts). At the same time, the economic efficiency of using restored bushings is determined by the lower cost of restoration technology.

The prospects of this research are the search for a more optimal phase and granulometric composition of the composition, as well as the application of more advanced technologies for the regeneration of spent coal inserts of current collectors of trolleybuses.

Conclusions

1. As a result of difficult operating conditions, coal current-carrying inserts of electric transport are subject to considerable wear. The causes of increased wear are electrocorrosion in contact with the conductor under current, abrasive wear from sliding on the wire with increased dustiness and air humidity.

2. Graphite is the main material used in friction pairs working in the sliding contact system, as it acts as a dry lubricant. Due to the limited wear resistance of pure graphite, there are many proposals for modifying the composition of contact sliding inserts in order to provide increased wear resistance, high anti-friction characteristics, and reduced electrical resistance.

3. One of the effective methods of introducing energy-saving technologies when using graphite inserts of electric transport is the secondary processing of the insert material for renewable use. The technological process of manufacturing graphite current-collecting inserts from spent graphite components has been developed. To improve the conductive properties of the inserts, it is suggested to add finely dispersed copper powder in the amount of 5% to the composition.

4. To prove the functionality of the restored current-collecting inserts, the strength, electrical conductivity and tribological characteristics of the material were tested. The results of experimental tests showed a slight decrease in material hardness and an increase in electrical resistance within acceptable limits. Bench wear tests showed improved tribological properties of the restorative insert material with the addition of copper powder.

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Ковтун О.С., Дитинюк В.О., Старий А.Л., Фасоля В.О. Відновлення та зносостійкість ковзних контактів електротранспорту

Електроконтактна вставка струмознімальної підвіски електротранспорту відноситься до швидкозношуючихся елементів, які потребують частої заміни і уваги щодо забезпечення нормативної працездатності. Метою цього дослідження була розробка технології виготовлення графітонаповнених електроконтактних вставок із відпрацьованих матеріалів та шляхом модифікації складу композиту. Внаслідок складних умов експлуатації вугільні струмознімальні вставки електротранспорту піддаються значному зносу. Причинами підвищеного зносу є електрокорозія в контакті із провідником під струмом, абразивний знос від ковзання по дроту із підвищеною запиленістю і вологістю повітря. Запропонований технологічний процес виготовлення графітових струмознімальних вставок із відпрацьованих графітових компонентів. Для доведення працездатності відновлених струмознімальних вставок були випробувані міцнісні, електропровідні та триболгічні характеристики матеріалу. Результати експериментальних випробувань показали незначне зменшення твердості матеріалу та збільшення електрично опору в допустимих межах. Стендові випробування на знос показали покращені трибологічні властивості відновного матеріалу вставок із додаванням порошку міді.

Ключьові слова: електротранспорт, струмознімач, контактна вставка, графіт, відновлення, спікання, зносотійкість, електричний опір

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Structural and energetic self-organization of antifriction composite materials of car parts during friction and wear

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Abstract

The development and research of composite materials for heavily loaded tribo-couplings of car parts was based on the main provisions of the concept of structural and energetic adaptability of their materials during friction and wear. The presented data of experimental studies of the effect of ultrasonic treatment of materials on the nature of the change in the coefficient of friction depending on the value of the specific load at a constant sliding speed. Data were obtained that characterize the features of structural adaptation and self-organization during friction and wear of copper and lead alloys. The research was carried out using a universal tribometer according to the "finger-disc" end surface contact scheme in the medium of inactive petroleum jelly. The use of composite wear-resistant materials is proposed to increase the tribological efficiency of car parts, units and assemblies. Experimental studies and analysis of the obtained data were carried out on the basis of the developed parametric scheme for the study of tribocouples of samples and parts using the main provisions of system analysis.

Key words: tribo coupling, tribometer, vehicles, alloyed composite materials, friction and wear.

Formulation of the problem

Increasing the serv DSS life of tribo couplings of car parts is one of the most important technical problems in the automotive industry. In this regard, the development of comprehensive measures to manage tribological efficiency is relevant. This is done in order to increase the operational reliability of the main working nodes, systems and aggregates. At the same time, they significantly reduce the cost of repairing the car and the production of spare parts, increase their operational reliability while achieving satisfactory technical, economic and environmental results. The durability of cars mainly depends on the nature of the friction and wear processes that occur in the contact zones between tribo coupling parts. Intensive wear of the working surfaces of the parts leads to a violation of the tightness of the nodes, a loss of accuracy in the placement and movement of the parts, which leads to jamming, shocks and vibrations, which in turn lead to mechanical breakdowns. The complex of energy, strength and kinetic conditions, mechanical and thermal parameters of self-organization is a single tribosystem with direct and feedback connections. The final result of the self-organization process is the formation of protective dissipative secondary structures (DSS) and the normalization of friction and wear indicators, which are characterized by the appropriate range and level. One of the promising directions for solving the problem of increasing the tribotechnical reliability of tribo-couplings of machines and mechanisms is the development of anti-friction composite materials and their comprehensive research based on the provisions of the structural and energetic adaptability of materials during friction and wear, self-organization of tribosystems, the theory of surface strength and destruction, taking into account the properties of these materials and conditions their operation in real nodes and mechanisms.

Analysis of recent research and publications

Solving the problem of increasing the tribological reliability and durability [1,2] of tribocoupled elements of car parts requires a comprehensive approach [3]. This includes: the following measures: development of modern research methods and kinetic criteria for evaluating processes in the zone of frictional contact; creation of new antifriction composite alloys; methods of controlling the surface strength of materials during friction and wear [4,5]. Intensification of processes in the zone of frictional contact leads to an increase in thermal and mechanical load on the tribocoupler [6], with corresponding negative consequences [7,8]. A systematic approach to solving this problem includes a complex of design, technological and operational measures for the development and research of alloyed composite antifriction materials [9,10] to increase the tribological reliability of heavily loaded car tribo couplings [11,12]. As pract DSS shows, it is difficult to achieve the necessary accuracy in quantitative indicators of initial parameters in laboratory, bench research of tribo-coupling, despite its significant economic, scientific, interdisciplinary importance for automotive engineering and technology in general. To date, the phenomenon of friction and wear has not been sufficiently studied. There is no unified theory of this process, there is no centralized bank of tribological data. As a result, there are no comprehensive recommendations for designers, technologists, and operators on increasing the tribological reliability and durability of friction units of machines and mechanisms. The application of the basics of system analysis allows you to get an answer to the question of the functional (technical) purpose of the considered tribological system, which is considered as a "black box" with the corresponding inputs, transformations and outputs.

The purpose of the work

The purpose of this work is the selection and comprehensive study of the tribological efficiency of the couplings of samples and parts made of composite alloys based on copper and lead, which were subjected to ultrasonic treatment, as well as alloyed composite alloys based on iron powder with the addition of copper powder and analysis of the nature of the change in the coefficient of friction from the specific load on triboconjugation of samples and parts, calculation of structural energy parameters: specific work of destruction A_r; energy capacity of the tribosystem according to the thermal index ECT_Q.

Research results

The work investigated the effect of ultrasonic treatment of alloys based on copper and lead (70,60,50% Cu + 30,40,50% Pb), as well as sintered compositions based on iron powders of the PZRV 2.200.28 brand with the addition of copper powder (respectively 2 ,4,6,8,10%) on the nature of the change in the coefficient of friction μ, the specific work of surface destruction A_r, the energy intensity of the friction system according to the thermal index ECT_Q depending on the value of the specific load p.

Tribological studies were carried out at the Department of Automobiles of the Ternopil National Technical University named after Ivan Pulyu on a complex of laboratory equipment, which includes: a tribometer, an automatic system for supplying lubricant to the friction zone, a measuring complex for recording the main tribotechnical indicators and parameters of the contact electrical resistance of tribocoupling [14] (Figure 1).

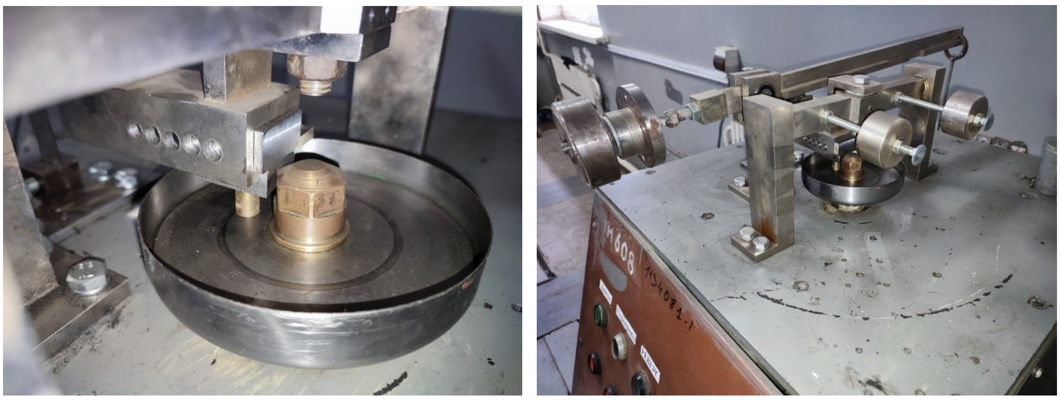


Fig. 1. General view of the tribometer friction assembly and loading mechanism

The research was conducted in an inactive petroleum jelly environment at a constant sliding speed of V = 0.35 m/s. The nature of the load on the test samples during the tests is smooth with fixation of the tested parameters at intervals of 1 MPa. The duration of the research process at each fixed load is 10 hours. A disk made of SHX15 steel (55...62 HRc, Ra = 0.63 μm) was used as a counterbody. The chosen planar scheme of tribo-coupling contact: the end surface of the disk (counterbody) - the end surface of the cylinder (sample). The structure and elemental composition of the friction surfaces were studied using a scanning electron microscope Cam Scan 4DV and the Link-860 system.

The results of the study of the influence of the specific load p on the coefficient of friction μ, the specific work of surface destruction A_r, the energy intensity of the friction system according to the thermal index ECT_Q of alloyed composite alloys based on copper and lead are presented in figures 2-4.

From the analysis of the obtained graphs, it follows that an increase in the content of Pb and its more uniform distribution in this alloy, under the influence of ultrasonic vibrations, contributes to the process of more intensive formation of internal combustion engines, which ultimately leads to an expansion of the range of normal friction and wear according to the load parameter p and a decrease in the value of μ.

The processes of grinding and uniform distribution of Pb in the alloy create favorable conditions for the formation of protective films of internal combustion engines on the friction surfaces of the samples, due to which their surface strength increases. The structural state of friction surfaces and the results of their microspectral analysis testify to the evolution of surface phenomena in the zone of frictional contact in the entire tribo-coupling load range. In this case, the presence of clear areas of structural adaptation of materials to operating conditions is typical.

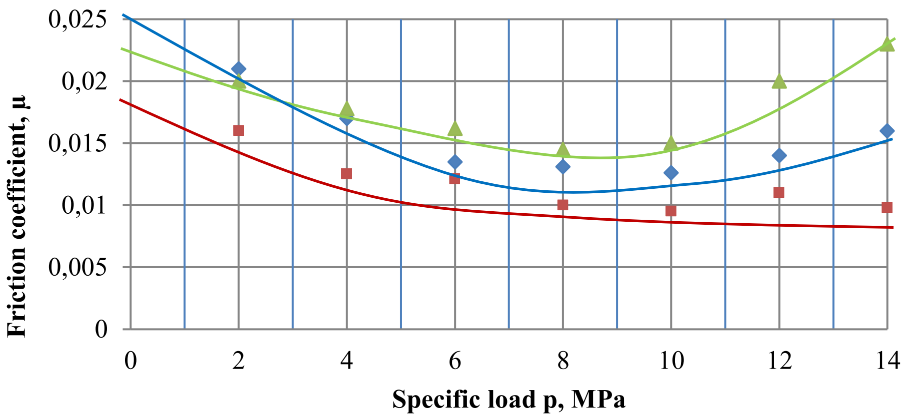


Fig. 2. The nature of the change in the friction coefficient μ from the specific load p:
♦ – alloy: (70% Cu + 30% Pb) ; ■ – alloy: (60% Cu + 40% Pb), ▲ – alloy: (50% Cu + 50% Pb)

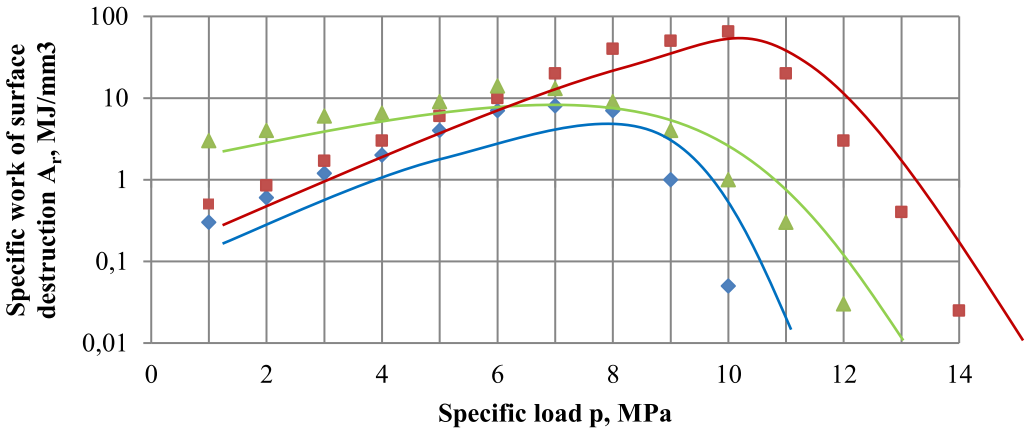


Fig. 3. The nature of the change in the specific work of surface destruction (A_r) from the specific load p:
♦ – alloy: (70% Cu + 30% Pb) ; ■ – alloy: (60% Cu + 40% Pb), ▲ – alloy: (50% Cu + 50% Pb)

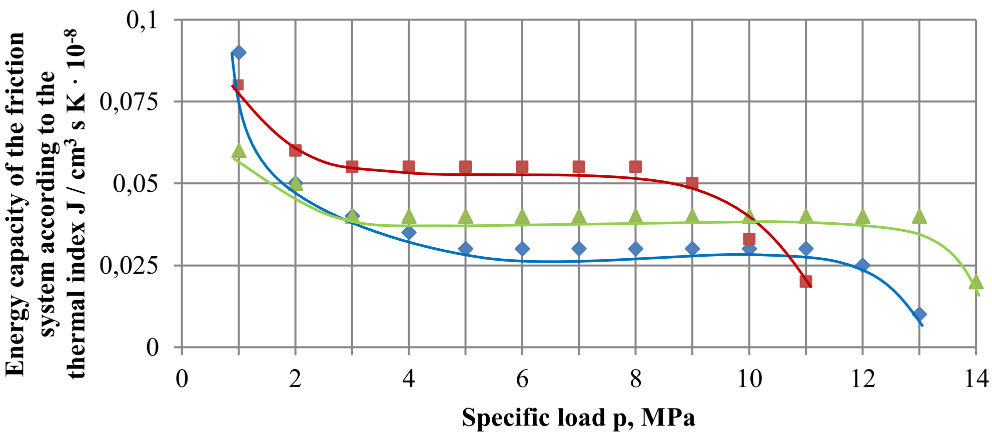
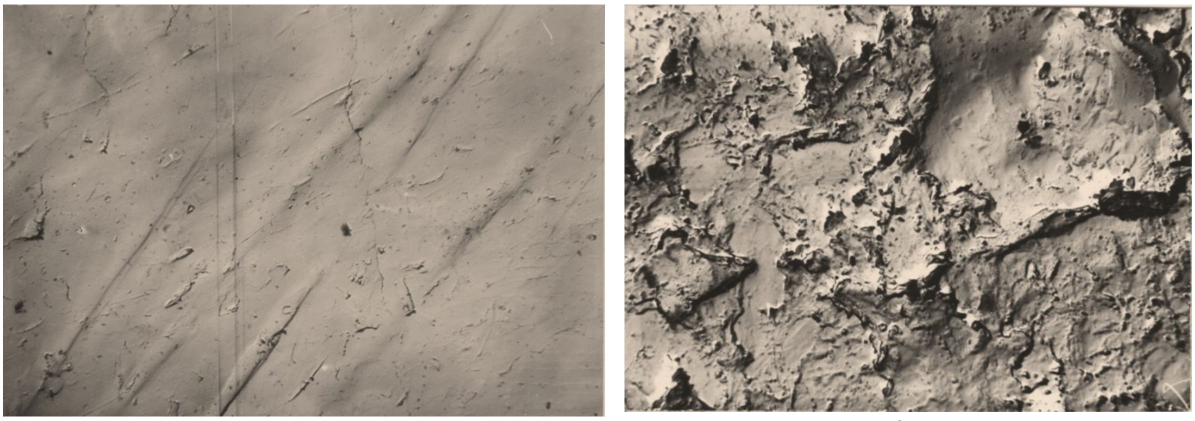


Fig. 4. The nature of changes in the energy capacity of the friction system according to the thermal index ECT_Q from the specific load p: ♦ – alloy: (70% Cu + 30% Pb) ; ■ – alloy: (60% Cu + 40% Pb), ▲ – alloy: (50% Cu + 50% Pb)

From the analysis of the data presented in the graphs (fig. 2-4) for all the studied materials, ranges are clearly distinguished, according to the power parameters of the load, in which the optimal (minimum and stable) value of the main tribotechnical indicators is fixed, with minimal dispersion - the range and level of normal friction and wear. Optimization of tribotechnical parameters is determined by the processes of formation, transformation and destruction of DSS types I and II [15].

The presence of friction on the surfaces of one or another type of internal combustion engine depends on the physical and mechanical properties of the starting materials, the lubricating medium, the lubrication regime, the nature of the change and the magnitude of the force parameters of the load, the scale factor, and others.

Fig. 5 presents electronic photos of the structure of the friction surfaces of the studied sample covered with DSS I (a) and DSS II (b) types (mode of normal friction and wear), and table 1 shows their main characteristics.



a b

Fig. 5. Electronic photographs of the friction surface of the studied alloy sample (50% Cu + 40% Pb) covered with DSS I (a) and DSS II (b)

For each metal and alloy, there are certain critical conditions of external mechanical influence and environment, under which DSS of one or another type is formed on the friction surfaces. This factor has a significant applied value for achieving fractional and anti-frictional states.

Table 1

Main characteristics of DSS I and DSS II types

Type of dissipative secondary structures	Roughness parameters Ra, µm	Depth of destruction, nm	The temperature of the surface layer °C, no more	Composition of the surface layer	Relative change in hardness of the surface layer	Type of destruction	The coefficient of increase in the volume of the surface layer	The speed of the destruction process, µm/g, no more
I	01-0,006	10-30	100	Solid solution and eutectics	2-3	Viscous	1 – 1,05	0,1
II	0,2-0,012	10-100	200	Oxides and eutectics	4-5	Viscous - fragile	1,05-1,08	0,05

Dissipative secondary structures have extreme anti-frictional (frictional) and strength characteristics, which normalize the processes of friction and wear of tribo-coupling samples, protect the original material of the parts' surfaces from mechanical and physico-chemical destruction.

Experimental samples for laboratory studies of iron-copper sintered compositions were made by the method of powder metallurgy. The mixtures were prepared on the basis of PZRV 2.200.28 iron powder. Depending on the copper content in the studied sintered compositions, their physical and mechanical properties are shown in fig. 6.

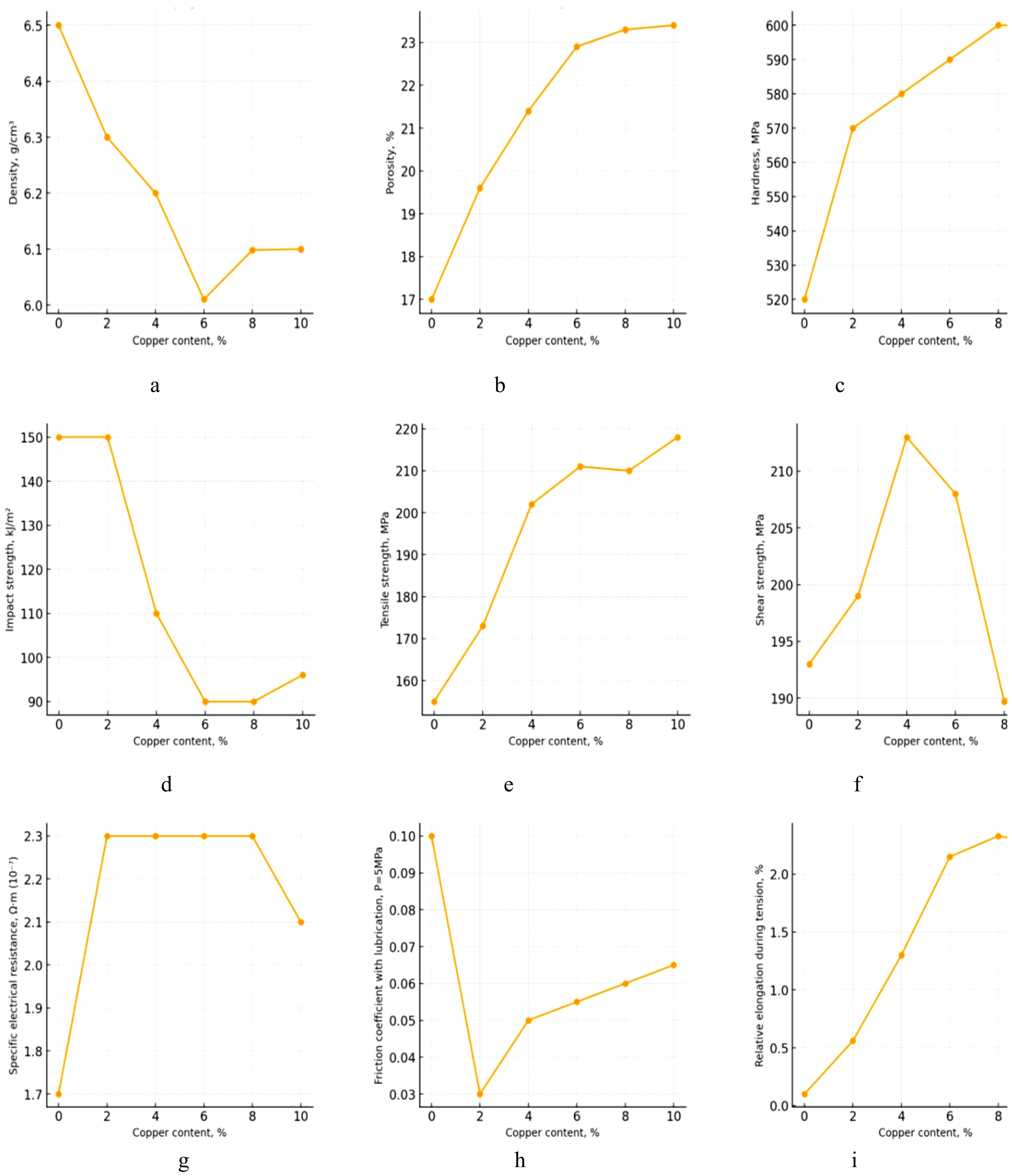


Fig. 6. Physical and mechanical properties of iron-copper compositions depending on the copper content: a - density, g/cm³, b - porosity, %, c - hardness, MPa, d - impact strength, kJ/m², e - tensile strength, MPa, f - shear strength, MPa, g - specific electrical resistance, Ω·m (10^{-7}), h - friction coefficient with lubrication, P=5MPa, i - relative elongation during tension, %

Laboratory (tribotechnical) studies of these compositions were carried out according to a similar tribo-coupling contact scheme. We investigated the mode of normal friction with the smooth nature of the change in the value of the specific load p (at a constant sliding speed v = 0.35 m/s) for a sample in the medium of inactive petroleum jelly. The results of tribotechnical studies are presented in fig. 7.

The graphs (Fig. 7) show areas characterized by stable values of the friction coefficient μ. At the same time, the indicated stability is typical both for pure iron samples (curve 1) and for compositions containing copper powder of different concentrations (curves 2-6). For sintered compositions that contain copper powders, there is a not DSS able decrease in the level of normal friction according to the μ parameter.

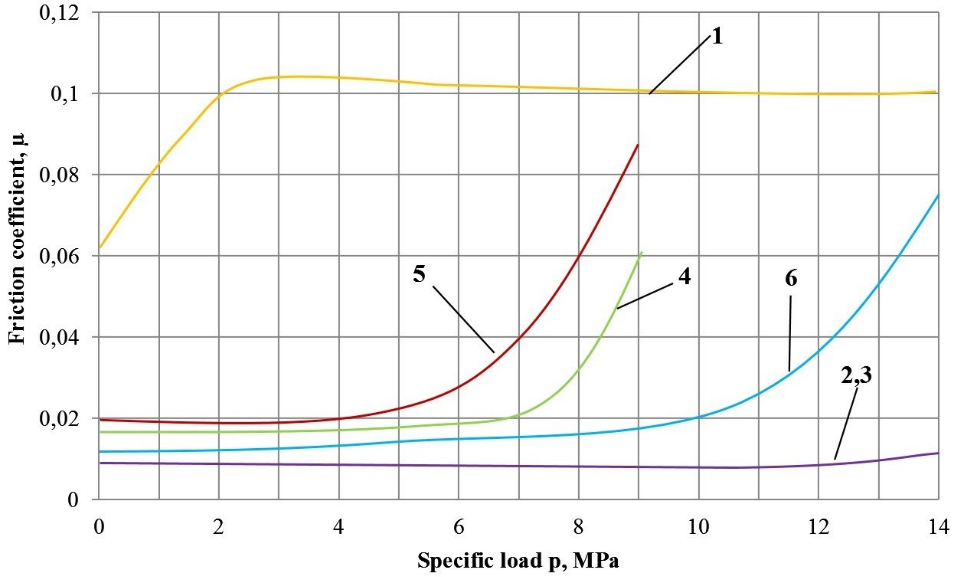


Fig. 7. The nature of the change in the coefficient of friction μ from the specific load p, for compositions with different Cu content, %: 1 – 0%; 2 - 2%; 3 - 4%; 4 - 6%; 5 - 8%; 6 - 10%.

When the critical values of the specific load p are reached, the output of the tribocoupler is fixed in the volumetric destruction mode (damage of the main material of the parts).

Conclusions

1. According to the research results, it was established that when the lead content in the Cu - Pb alloy changes (respectively 30, 40 and 50%) and its uniform distribution under the influence of ultrasonic treatment, the main tribotechnical indicators of the friction and wear process improve. In the mode of normal mechano-chemical friction and wear, this leads to an expansion of the range and a decrease in the level of structural adaptability of this alloy with the formation of the corresponding DSS I or DSS II types on the friction surfaces.

2. When adding copper powders of various concentrations to the composition of sintered compositions based on PZRV 2.200.28 iron powder, the tribotechnical indicators of heavily loaded tribo couplings are improved, which is due to the structural rearrangement of the friction surfaces and the appearance of anti-friction copper films on them, which realize the process of normal friction and wear in a wide range of force load with a decrease in the level of self-organization according to the μ parameter.

3. Informative, from the point of view of tribological research and analysis of the obtained results, are the structural and energy parameters A_r - the specific work of surface destruction and the energy intensity of the friction system according to the thermal index ECT_Q, which characterize the relationship between the values of the main tribotechnical parameters, the kinetics of friction processes and wear, structural state of friction surfaces (internal combustion engine type), mechanisms of their formation, transformation and destruction.

4. The practical operation of the universal tribometer during laboratory studies confirmed its reliability and efficiency, the satisfactory comparability of the obtained results, the high rigidity of the friction unit and the load mechanism, the absence of vibration, a wide range of force parameters of the load with their smooth change, the reversible nature of the movement, the openness of the friction unit for visual control, a convenient shape of the friction working surface of the sample for further studies of the structural state.

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Гупка А.Б., Аулін В.В., Міронов Д.В., Лещук Р.Я., Ярема І.Т., Буховець В.М., Тесля В.О.
Структурно-енергетична самоорганізація антифрикційних композиційних матеріалів деталей автомобілів при терті та зношуванні

Розробка та дослідження композиційних матеріалів для важконавантажених трибоспряжень деталей автомобілів базувались на основних положеннях концепції структурно-енергетичної пристосовуваності їх матеріалів при терті та зношуванні. Наведенні дані експериментальних досліджень впливу ультразвукової обробки матеріалів на характер зміни коефіцієнта тертя в залежності від величини питомого навантаження при постійній швидкості ковзання. Отримано дані, які характеризують особливості структурної адаптації та самоорганізації при терті та зношуванні сплавів міді та свинцю. Дослідження проводили з використанням універсального трибометра за схемою контакту торцевих поверхонь «палець-диск» у середовищі інактивного вазелінового мастила. Запропоновано використання композиційних зносостійких матеріалів для підвищення трибологічної ефективності деталей, вузлів та агрегатів автомобілів. Експериментальні дослідження та аналіз одержаних даних проводили на базі розробленої параметричної схеми дослідження трибоспряжень зразків і деталей з використанням основних положень системного аналізу.

Ключові слова: трибоспряження, трибометр, транспортні засоби, леговані композиційні матеріали, тертя та зношування.

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The influence of boron carbide clad with a nickel-based alloy on the abrasive wear rate of aromatic polyamide phenylon

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Abstract

The paper presents the results of the development of new composite materials based on aromatic polyamide phenylon, filled with dispersed boron carbide and clad with PKHN-15 alloy. The influence of the percentage content of the filler on the abrasion rate under the conditions of friction with rigidly fixed abrasive particles was studied. It is shown that the degree of filling determines the rate of abrasive wear of composites, which reaches a minimum at a filler content of 25 wt.%. The introduction of boron carbide clad with the PKHN-15 alloy leads to a decrease in the abrasion rate of the aromatic polyamide phenylon by 6.2-9 times, which correlates with the strength indicators. The roughness of the composites is almost at the same level, from which we can conclude that the amount of filler affects their wear mechanism. An increase in microhardness at the boundary of the "polymer-filler" separation was noted, which may indicate the presence of interaction between the polymer and the filler. It is shown that the abrasive wear rate for composites containing 10-15 wt.% filler is more stable than for composites with a larger amount of filler. Developed composites are recommended for work in friction units operating in abrasive conditions, or as working bodies of grain harvesting machines and mechanisms that are in constant contact with grain which acts as an abrasive for working surfaces.

Keywords: aromatic polyamide phenylon, clad PKHN-15 alloy, abrasive wear rate, microhardness

Introduction

Today, one of the main reasons for reducing the service life of systems and units of transport vehicles equipped with serial metal parts is the abrasive wear of the working surfaces of tribological joint parts [1]. More than 30% of the world's energy costs fall on the elimination of the consequences caused by abrasive wear. Therefore, the development and introduction of new materials with high indicators of abrasive wear resistance into production is an urgent task for materials science. A promising way to solve this problem is the use of polymer composite materials (PCMs). Thanks to their high self-lubricating ability, PCMs allow us to abandon the use of lubricating and cooling fluids and high-performance oils in the operation of tribological units, which in turn leads to a reduction in financial costs for equipment maintenance. As the analysis of literary sources [2, 3] showed, PCMs are superior to carbon steels and non-ferrous metals in terms of functional properties. The use of PCMs in the tribological joint parts of the seeding complex and cultivators for processing agricultural crops, manure-removing scraper conveyors, plate chains of tow trucks increased their working life up to 5 times while simultaneously reducing labor costs for maintenance. It is important to note that the production of PCMs parts (even of complex configuration) leads to the formation of 10-30% of waste, which is much less compared to parts made of high-strength aluminum and titanium alloys. In the agricultural and metallurgical industry, waste from the production of such metal parts can exceed the weight of the product by 4-12 times. At the same time, the waste generated during the production of PCMs parts can be recycled, which is why PCM is considered an ecological material.

Dispersed powders of metals and carbides are one of the effective fillers for creating wear-resistant PCMs. The use of powders of copper (Cu), aluminum (Al), nickel (Ni), PR-N65 H25S3R3 self-fluxing alloy, boron carbide, titanium-tantalum-tungsten-cobalt (TTC) alloy allows to create PCM characterized by high indicators of thermal conductivity, wear resistance under the influence of abrasive particles, high self-lubricating properties in conditions of high-speed sliding, resistance to the influence of dynamic and fatigue loads [3, 4-6].

The purpose of the work

Considering the above, this work is aimed at the development and research of new PCMs with high indicators of wear resistance.

Objects and methods of research

C-1 aromatic polyamide phenylon (APP) was chosen as a polymer matrix for creating wear-resistant PCMs. Among the large number of engineering and technical materials, polyamides and composites based on them continue to occupy one of the important places in many branches of modern industry due to high indicators of functional properties and the possibility of forming products by many methods (die casting, compression pressing and 3D printing). It is known [3] that APP is characterized by high temperatures of long-term and short-term operation, low wear, increased radiation, corrosion and chemical resistance. Thanks to this, APP is mainly used for the production of parts that work in harsh operating modes.

Dispersed powder of PKHN-15 alloy with an average particle size of 40-100 μm based on chromium carbide clad with 15% of nickel was chosen as a FL. The use of clad alloys, which are characterized by a complex of unique properties and have an active surface, leads to a change in the interaction between the polymer and the FL, and, as a result, to an increase in adhesion between them. Thus, it is possible to expect an increase in the physical and mechanical characteristics of compositions containing clad alloys as a filler. Production of new PCMs based on APP was carried out according to the method given in the paper [7].

The study of the resistance of the developed PCMs and pure PA to the influence of hard-fastened abrasive particles (dispersion is 100 μm) was carried out using a HECKERT test machine. Before the start of the experiment, each test sample underwent a preliminary run-in in the usual mode until its surface was in full contact with the abrasive skin. The load on the sample was 10 N, and the length of the friction path for one test cycle was 40 meters. A comparison of the morphology of the friction surfaces of APP and PCMs based on it was carried out using a BIOLAM-M microscope at a magnification of 200. Microhardness at the boundary of the "polymer-filler" separation was determined using a PMT-3M device. Hardness was determined on a hardness tester 2074 ТПР.

Results

The analysis of the results of the friction of composites carried out using rigidly fixed abrasive particles (see Table 1) showed that the degree of filling directly affects the abrasive wear rate of composites. This indicator reaches its minimum value at a filler content of 25 wt.%. The introduction of harder filler into the polyamide matrix contributes to the strengthening of the composite material and inhibits the development of deformation processes in the matrix during abrasion, which increases the wear resistance of the developed materials.

Table 1

Functional properties of aromatic polyamide phenylon and composites based on it

Indicator	Percentage content of PKHN-15 alloy, wt.%				
	0	10	15	20	25
Average rate of abrasive wear, V, mm^3/m	1,80	0,29	0,27	0,25	0,20
Hardness, HB, hardness units	80,00	85,00	86,00	89,00	90,00
Roughness, Ra	1,15	0,99	0,87	0,99	1
Microhardness at the boundary of the "polymer - filler" separation, HV, hardness units	-	172,0	193,5	225,6	171,7

The introduction of boron carbide clad with the PKHN-15 alloy significantly reduces the rate of abrasive wear of aromatic polyamide phenylon by 6.2-9 times. This decrease is directly correlated with an improvement in the hardness of the material. Thus, the addition of clad boron carbide not only increases the wear resistance, but also significantly increases the hardness of the composite.

It is worth noting that the surface roughness of the composites remains practically at the same level regardless of the amount of added filler. This allows us to conclude that the wear mechanism does not change with the change in the amount of filler. This is an important aspect because stable roughness ensures predictable behavior of the material in service.

In addition, there is a significant increase in microhardness at the polymer-filler interface. This indicates the possible presence of interaction between the polymer and the FL. Such an interaction can contribute to the improvement of adhesion between the components of the composite, which additionally increases its strength and wear resistance.

Studies of the dependence of the abrasive wear resistance of composites on the number of cycles are shown in fig. 1. It can be seen from the given data that with an increase in the number of cycles, the wear resistance of all investigated composites becomes practically identical. At the same time, the indicator is more stable for composites containing 10-15 wt.% FL than for composites with a larger amount of the FL. This can be explained by a decrease in the plasticity of the composite due to the appearance of a large number of FLs, due to which the filler breaks out of the surface layers of the composite under the action of abrasive particles. The voids formed as a result can be seen in fig. 2 c, d, where the friction surfaces of the studied composites are shown.

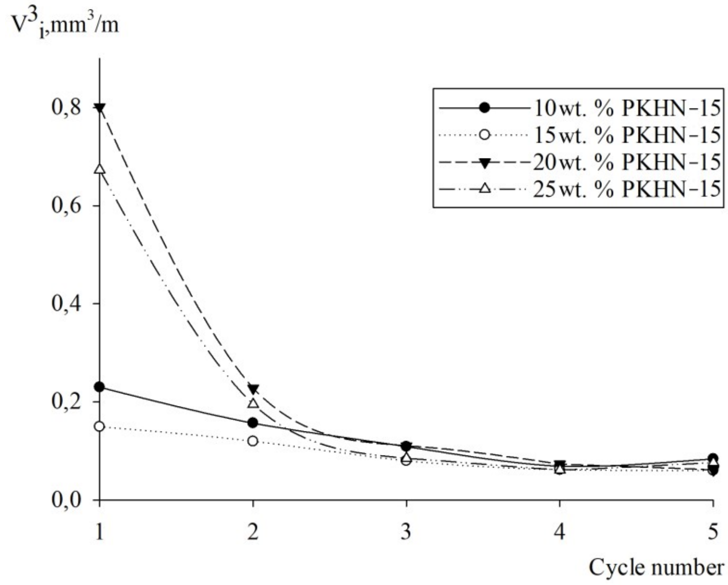

Fig. 1. Dependence of abrasive wear resistance of composites on the number of cycles

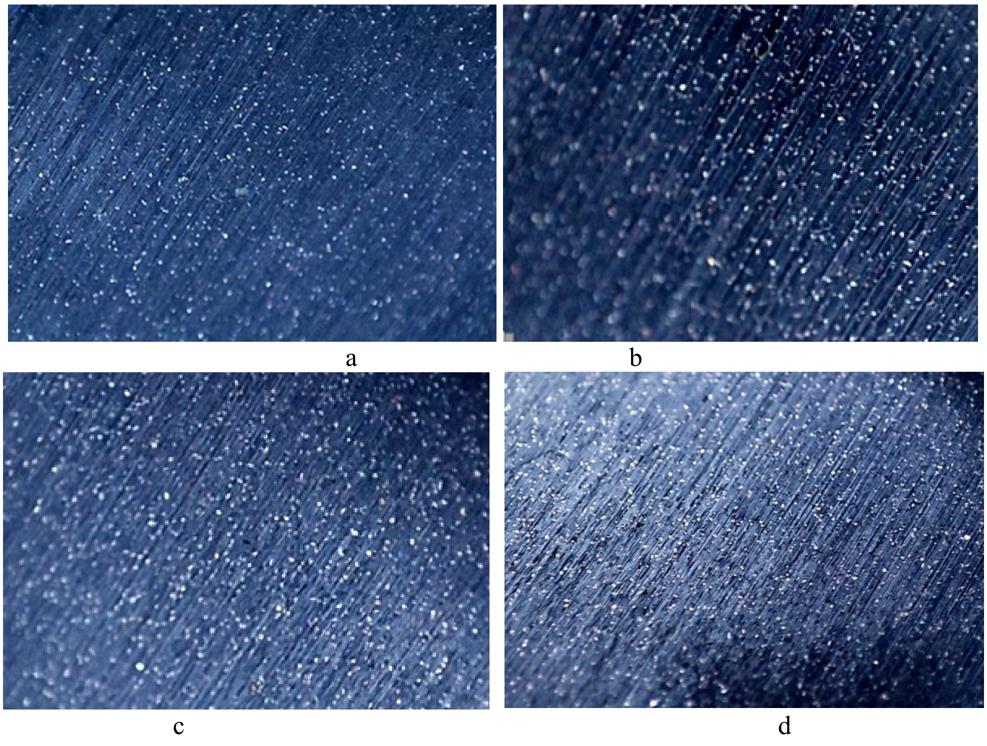

Fig. 2. Friction surfaces of composites containing: a – 10, b – 15, c – 20, d – 25 wt.% boron carbide clad with PKHN-15 alloy

The friction surfaces have a grooved structure, which is formed as a result of the ploughing process. It is important to note that no microcracks are observed on these surfaces, which is evidence that the material undergoes mainly plastic failure under the influence of sliding friction, that is, the surface layer is deformed and is more susceptible to stretching and crumpling than cracking, which leads to the formation of grooves. This type of destruction is typical for materials that are characterized by satisfactory plasticity and are capable of deformations without the formation of cracks.

The results of the conducted research indicate that the developed composites containing boron carbide clad with PKHN-15 alloy are promising materials for use in friction units operating in abrasive conditions. Boron carbide is known for its high hardness and wear resistance, making it an ideal component for materials subject to heavy wear. The PKHN-15 alloy, which is clad with boron carbide, provides additional properties, such as corrosion resistance and self-lubricating ability, which increases the overall performance of the composite.

These composites can be effectively used in various engineering and industrial applications, especially in friction units operating in abrasive conditions. For example, they can serve as working bodies of grain-harvesting machines and mechanisms that are constantly in contact with grain. The grain, which is an abrasive material, can quickly wear out the working surfaces of ordinary materials, but composites with boron carbide and PKHN-15 alloy can significantly extend the service life of such mechanisms.

The use of such composites will help reduce the frequency of replacement of worn parts, increase the reliability and efficiency of equipment, and reduce maintenance and repair costs. This is especially important in agriculture, where equipment downtime can lead to significant crop losses.

Conclusions

Summing up the results given in the article, the following conclusions can be drawn:

– New composite materials based on aromatic polyamide phenylon filled with dispersed boron carbide clad with PKHN-15 alloy were developed and can be effectively used in various engineering and industrial applications, especially in friction units operating in abrasive conditions.

– The influence of the percentage content of the filler on the abrasive wear rate under the conditions of friction with rigidly fixed abrasive particles was studied and it was shown that the rate of abrasive wear of composites reaches a minimum with a filler content of 25 wt.%.

– It is shown that the introduction of boron carbide clad with PKHN-15 alloy leads to a decrease in the abrasion index of aromatic polyamide phenylon by 6.2-9 times

– An increase in microhardness at the boundary of the "polymer-filler" separation was noted, which may indicate the presence of interaction between the polymer and the FL.

– It is shown that the rate of abrasive wear is more stable for composites containing 10-15 wt.% FL, compared to composites with a larger amount of the FL.

– Developed composites are recommended for work in friction unites operating in abrasive conditions, or as working bodies of grain harvesting machines and mechanisms that are in constant contact with grain acting as an abrasive for working surfaces.

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Єрьоміна К.А., Томіна А.-М.В., Яровий Я.Є. Вплив карбіду бора плакованого сплавом на основі нікелю на показник абразивного стирання ароматичного поліаміду фенілон

У роботі наведено результати розробки нових композиційних матеріалів на основі ароматичного поліаміду фенілон, наповненого дисперсним карбідом бору плакованого сплавом ПКХН-15. Досліджено вплив відсоткового вмісту наповнювача на показник абразивного стирання в умовах тертя жорсткозакріпленими абразивними частками. Показано, що ступінь наповнення визначає показник абразивного зношування композитів, який досягає мінімуму при вмісті наповнювача 25 мас.%. Введення карбіду бора плакованого сплавом ПКХН-15 призводить до зменшення показника абразивного стирання ароматичного поліаміду фенілон у 6,2 – 9 разів, що корелює з показниками міцності. Шорсткість композитів знаходиться практично на одному рівні, з чого можна зробити висновок, що кількість наповнювача на впливає на їх механізм зношування. Відзначено збільшення мікротвердості на межі поділу «полімер-наповнювач», що може свідчити про наявність взаємодії між полімером та наповнювачем. Показано, що для композитів, що містять 10 – 15 мас.% наповнювача, показник абразивного стирання більш стабільний, ніж для композитів з більшою кількістю наповнювача. Рекомендовано розроблені композити для роботи у вузлах тертя, що працюють у абразивних умовах, або як робочі органи зернозбиральних машин та механізмів, що постійно контактують із зерном, яке виступає як абразив для робочих поверхонь.

Ключові слова: ароматичний поліамід фенілон, плакований сплав ПКХН-15, показник абразивного стирання, мікротвердість

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Influence of factors of the electric arc spraying process on the properties of coatings

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Abstract

The article discusses primary (technological factors) relating to the technology and conditions of spraying and secondary ones, which are derived from technological factors affecting the structure formation and properties of coatings. The paper examines the influence of spraying distance, dispersion of sprayed particles, wire material, etc. on the properties of electric arc coatings. Summarizing the results of research on the influence of factors of the electric arc spraying process on the structure formation and properties of coatings, the parameters of the electric arc spraying process were established, the method of preparing the surface before spraying was selected, etc. method of processing sprayed coatings.

Key words: electric arc spraying, properties, structure formation, technological factors, coatings, microhardness, density, adhesion strength

The state of the problem and the purpose of the research

In the practice of strengthening and restoring parts, the method of electric arc spraying (EAS) has become widespread as one of the most technologically advanced, productive and high-quality methods. The widespread use of electric arc spraying is facilitated by a number of significant advantages over other methods:

– high productivity of coating up to 20 kg/hour of steel, up to 10 kg/hour of aluminum;
– obtaining a coating thickness from 0.1 to 10 or more millimeters;
– wear resistance is 1.5-1.8 times higher than hardened steel 45, which is due to good oil absorption and oil retention in the micropores of the coating;
– the ability of coatings to work normally without access to lubricant until setting;
– ensuring the wear resistance of parts at the level of new ones;
– there is no deformation of parts, which is inevitable during surfacing, since during electric arc spraying there is insignificant heat input (heating temperature of the part is 100-150° C);
– simplicity and manufacturability of the process;
– the possibility of coating the surfaces of parts made of various materials (steel, cast iron, aluminum, bronze, wood, polymer, etc.);
– the dimensions of the parts do not limit the use of electric arc spraying;
– production of combined metal coatings with specified properties from various wire materials;
– low specific cost of coating application (1.4-1.8 times lower than surfacing).

The positive qualities of EAS (manufacturability, simplicity, high productivity and wear resistance, absence of thermal leads, low cost and versatility, stability of the fatigue strength of restored parts) could not go unnoticed by scientists and production workers.

However, the electric arc spraying method, like any metal coating method, also has disadvantages. The main disadvantage has always been considered to be the low adhesion-cohesive strength of the coating. The second factor limiting the use of EAS was the low hardness of the coating compared to surfacing.

Despite the large number of developments in the field of electric arc spraying (EAS), research is actively developing at the present time, and it has become focused on rational activation of the process or subsequent modification.

The aim of the work - study of the influence of factors and modes of the electric arc spraying process on the properties of coatings.

Factors influencing the structure formation and properties of coatings

The electric arc spraying (EAS) is characterized by a large number of factors that influence the structure formation and properties of coatings. It is advisable to distinguish primary (technological factors) related to technology and spraying conditions and secondary ones, which are derived from technological factors.

It is advisable to include the following as primary factors:

– factors relating to spraying modes: the magnitude of the welding current, the type, pressure and flow rate of the spraying gas, the diameter and shape of the nozzle;

– factors relating to spraying conditions: design of the blowing system; spraying distance, metallizer movement speed;

- factors relating to the sprayed material: wire diameter, chemical composition and structure of the wire, wire feed speed;

– factors relating to the preparation conditions of the sprayed surface: material, preparation method, surface roughness, heating temperature.

– factors relating to the processing of sprayed coatings.

The above primary factors determine the secondary factors that influence the kinetics and structure formation of coatings. These include: diameter, speed and temperature of particles, their degree of oxidation; degree of activation, roughness and temperature of the substrate. It should be noted that the influence of most factors on the EAS process has been studied by various researchers.

Research into the influence of electric arc spraying modes on the quality and properties of coatings

The quality of coatings and properties largely depend on the pressure of the atomizing gas and the spraying distance. Most researchers agree that increasing pressure increases coating adhesion and reduces porosity.

Studies of the influence of electric arc spraying modes on the properties of coatings show (Fig. 1) that the adhesion of the coating with an increase in the air flow rate, and, consequently, the jet flow rate, increases, and porosity decreases [1- 4]. When air flows at subsonic speed, the size of the molten particles averages 200 microns. As the air flow rate increases, 90% of the molten particle size is in the range of 30–80 µm. However, such a decrease in the size of the molten particles of the sprayed material leads to more intense burning of alloying elements from them, primarily carbon, which causes increased hardness of the coatings at subsonic air flow velocities. The content of the remaining alloying elements of the wire changes to a lesser extent with an increase in the speed of air flow from the metallizer and the arc discharge current [2].

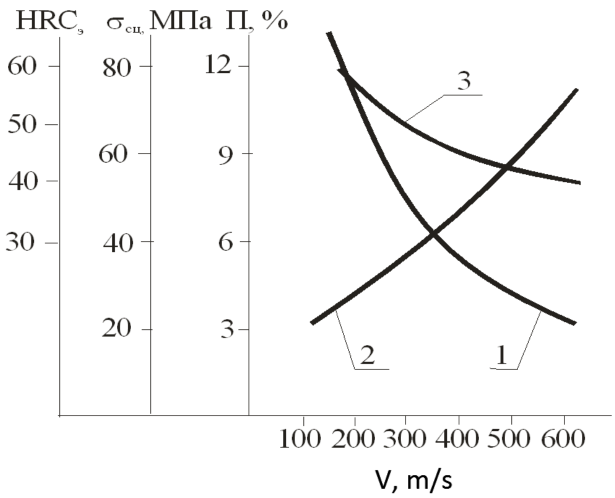


Fig. 1. Influence of air flow velocity from the nozzle (V, m/s) on the properties of coatings during electric arc spraying (EAS): 1 - porosity (P,%); 2 - adhesion strength (σ_{adh}, MPa); 3 - hardness (HRC_e)

One of the important technological factors in electric arc spraying (EAS) is the spraying distance. On the one hand, increasing the distance helps to increase the speed of particles, on the other hand, it leads to increased oxidation of the particle and a decrease in its temperature. The optimal range of spraying distance according to research [3] is in the range of 80...150 mm (Table 1).

Table 1

Properties of coatings depending on the spraying distance

Coating properties	Distance from nozzle to part, mm						
	30	50	75	100	120	200	300
Adhesion strength, MPa	15	18	19	21	22	22	19
Oxide content in the coating, %	10	12	13	15	16	25	30

By improving the design of equipment for electric arc spraying and increasing the protective energy level of the spray torch, the problem of increasing the physical and mechanical properties of coatings was solved by reducing the oxidation of dispersed metal in the spray torch and increasing the flight speed of particles. To apply coatings, devices with different blowing systems and nozzle geometries are used. Work [4] notes the advantage of devices with a closed circuit and a differential nozzle compared to an open circuit of a central nozzle. Therefore, the research in this dissertation was carried out on an EM-14 metallizer with a diaphragm nozzle.

Sprayed materials and their connection with the properties of coatings

For electric arc spraying (EAS), the use of any type of wire produced by industry is technologically possible. When spraying low-carbon unalloyed wire materials, the coating has a low level of mechanical properties. The hardness of the metal and oxides is different and amounts to 210...280 HV and 400...560 HV, respectively. The coating is characterized by high internal fragility due to the presence of a large amount of oxides (up to 20%), a high coefficient of friction f = 0.4...0.6 and low wear resistance [1, 3]. The adhesion strength to the substrate does not exceed 22...24 MPa. The porosity of the coating is in the range of 13...18%. The structure of the coatings is a layered system consisting of elongated grains (lamellas), the phase composition of which corresponds to a solid solution of chromium in α-iron, with finely dispersed inclusions of complexly alloyed boride compounds of chromium and iron.

As noted in the literature [5-9], relatively high properties of coatings using electric arc spraying (EAS) are achieved by using composite flux-cored wires. An analysis of the problems of strength and wear-resistant properties of coatings also led to the conclusion that it is necessary to use flux-cored wires for electric arc spraying (EAS). Composite flux-cored wires are most widely used (sheath made of steels Sv-08, Sv-08G2S, 30KhGSA, Steel 70, U8, U10, 20Kh13,40Kh13, 65G, filler - ferroalloys, carbides, carboborides).

These include FMI-2 flux-cored wire developed by scientists from the Physico-Mechanical Institute named after G.V. Karpenko NAS of Ukraine (Lviv, Ukraine). Protection against oxidation and high properties of coatings are achieved through the interaction of the components of the powder mixture with each other, while the processes of oxide reduction and alloying of the steel base occur. The content of ferrochrome 16-19% and aluminum 14-17% in the flux-cored wire provided a significant increase in adhesive-cohesive strength. Hardness 50-58 HRC. Coatings obtained by spraying flux-cored wires have greater hardness and wear resistance.

The practice of using flux-cored composite wires in gas-thermal spraying shows that the performance properties of coatings made from flux-cored wires are higher than those made from homogeneous ones. The advantages of flux-cored wires are determined not only by the heterogeneous structure of the coating after spraying, but also by the active interaction of the components of the powder mixture with each other during spraying and with the substrate, which contributes to an increase in the temperature of the particles, deoxidation of oxides on the surface of the substrate, and as a result, increased adhesion of the coating to the substrate.

However, our research has shown that with increasing carbon content in the sprayed composite wire, the mechanical properties of the coating increase, and the adhesion strength decreases slightly. When spraying U8 steel, the coating hardness is 360...380 HV, the adhesion strength is 18...20 MPa.

Alloyed and highly alloyed wire materials make it possible to obtain the best properties of electric arc spraying (EAS) coatings from all homogeneous wire materials. A significant increase in properties is due to the strengthening effect of alloying elements in steel.

Chromium helps, with rapid cooling, to increase the hardenability of steel, therefore the structure of coatings made of chromium steels consists mainly of martensite and its tempering products. With a significant chromium content in the original wire, $Cr_{23}C_6$ carbides are formed in the coating, as well as a small amount of austenite. Chromium significantly increases the corrosion resistance of coatings, as well as the adhesion of the coating to the lubricant. Chromium in its pure form does not affect the adhesion strength of coatings. During electric arc spraying, chromium practically does not burn out [1].

Nickel is widely used in alloys for protective coatings. It is unlimitedly soluble in iron and is a strong austenitizing element [1]. Nickel does not form its own high-hard phases in iron alloys. Its effect is to significantly increase the resistance of coatings to impact loads. With increasing nickel content, the toughness of the alloy increases with virtually no loss of wear resistance. Nickel is an expensive alloying element, so its amount in wear-resistant iron-based alloys is limited. The exception is alloys for corrosion-resistant coatings. In self-fluxing powders, nickel is used as the alloy base. In this case, high corrosion and wear resistance, as well as manufacturability of coating application, are achieved due to the formation in the M-Cr-B system of a heterogeneous structure of the eutectic type with a low melting point (less than 1000°C).

However, high-alloy wire materials are close in cost to flux-cored wire materials, however, they are inferior in efficiency (Table 2).

According to research, the diameter of the wire used during electric arc spraying (EAS) affects the conditions for the formation of a metal-air jet. In [2-4], an increase in jet turbulence is noted when the wire diameter increases to more than 1.8 mm, as well as an increase in the pressure drop in the area where the wires cross. When the wire diameter decreases to less than 1.2 mm, a deterioration in process stability is observed due to the variability of the position of the wire crossing point. The optimal range of diameters is 1.2...1.8 mm.

The influence of the method of surface preparation during electric arc spraying (EAS) on the adhesion strength and the effective stress concentration coefficient. Pre-treatment of the sprayed surface is necessary to ensure reliable contact of the sprayed material and the base metal by activating the surface layer of the base and removing contaminants. Preliminary surface treatment of the base metal is carried out using a variety of technological methods. At the first stage of surface preparation, degreasing is carried out to remove various contaminants. Next comes mechanical surface treatment. Among all the methods, the most productive are shot processing, sand blowing, cutting torn threads, and applying various forms of notches.

Table 2

Technical and economic characteristics of common grades of steel wire materials

Wire brand	Chemical composition	Purpose	Hardness after spraying, HV
Sv-08	C-0,08...0,1%	welding of low carbon steels	250...300
Sv-08G2S	C-0,08...0,1%, Mn-1,5...2,0%, Si-0,8...1,2%	welding of low carbon steels	250...300
Surfacing wire Np 40	C-0,37...0,42%	wear-resistant surfacing of machine parts	300...350
Surfacing wire Np 60	C-0,57...0,62%	wear-resistant surfacing of machine parts	350...400
65G	C-0,63...0,68%, Mn-0,8...1,2%,	wear-resistant surfacing of machine parts	350...400
U8	C-0,76...0,82%	wear-resistant surfacing of machine parts	360...400
20Kh13	C-0,18...0,22%, Cr-11...13%	wear-resistant surfacing of machine parts	360...420
Flux Cored Wire PP-TP1 (powder)	C-0,67%, Cr-3,58%, Ni-2,33%, Si-0,27%, Mn-0,42%, Al-2,08%	electric arc spraying and surfacing of tribo-joint parts	400...450
Surfacing wire NP-4 (powder)	Alloying system Fe-C-B-Cr	electric arc spraying and surfacing of tribo-joint parts	400...450

Shot treatment before spraying provides high adhesion (Table 3), increasing the endurance limit of the base metal. Therefore, during the research, the samples were subjected to shot blasting with steel chips.

Table 3

Influence of the method of surface preparation during electric arc spraying (EAS) on the adhesion strength and the effective stress concentration coefficient

Method of preparation	Strength of adhesion to the base, MPa	Effective stress concentration factor [6]
Shot processing	22	0,78
Sand blasting	20	0,91
Threading	23	1,3
Notching	22	1,29
Electrospark	23	1,08

Results of experimental studies

At the first stage of the research, the distribution of particles obtained by spraying flux-cored wire into fractions was assessed (Table 4, Fig. 2).

Since the largest fractions have a minimal share in the overall distribution pattern, it would be expected that the sprayed layers would be quite dense.

The structure of the sprayed coating was a heterophase system consisting of two or more phases separated by an interface and differing in chemical composition and properties.

Table 4

Mass fraction of particles of different fractions

№	Fraction, mm	Weight, g	Mass fraction, %
1	более 0,63	0,081	0,1
2	0,63…0,40	1,204	1,52
3	0,40…0,315	1,012	1,28
4	0,315…0,20	11,930	15,14
5	0,20…0,16	11,000	14
6	0,16…0,10	22,021	28
7	0,10…0,063	21,450	27,25
8	Менее 0,063	10,012	12,7

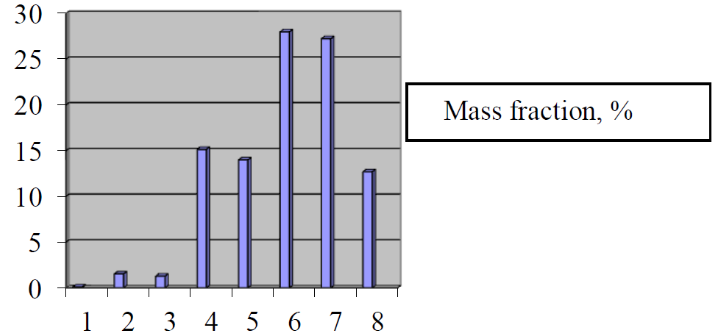


Fig. 2. Histogram of the distribution of the mass fraction of particles of different fractions

Molten particles transported by a high-speed jet of combustion products are flattened and mixed during their collision with the surface of the substrate. As a result, a specific, wavy microstructure with residual porosity is formed. The sprayed coating had a lamellar structure of crystallized particles of metal, oxides and powder filler, and the oxides are located, as a rule, along the boundaries of the lamellas (Fig. 3). As follows from the results of studying the fractional composition of particles of atomized flux-cored wire, the coatings had a fairly high density (porosity did not exceed 12-14%). Research carried out on a JSM-840 electron microscope and a MeF-3 light microscope from Reichert (Austria) showed that the powder particles included in the sprayed wire in the form of filler are fully or partially preserved. Figure 3 shows a fragment of a coating obtained by spraying FMI-2 flux-cored wire.

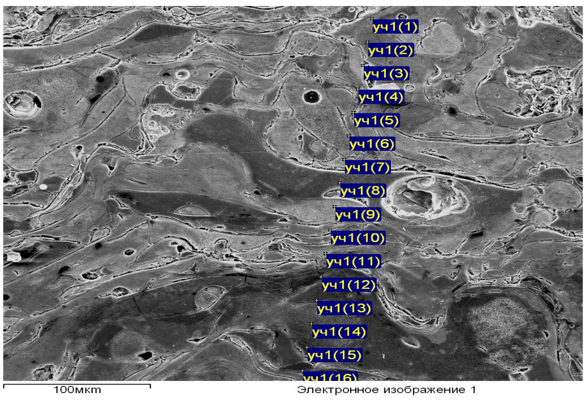


Fig. 3. Structure of the coating obtained by electric arc spraying of FMI-2 flux-cored wire

Processing of sprayed coatings

Predicting the appearance of possible structural features and physical and mechanical properties of gas-thermal coatings modified by electrical contact processing based on data obtained from electrical contact processing of loosely poured powders or layers formed by the adhesive method is impossible, which is associated with the following features of sprayed coatings:

– ultra-fast crystallization of sprayed melt droplets leads to a high concentration of crystal lattice defects (dislocations, vacancies) in the coating particles;

– the coating particles have a structure that reflects the condition of heterogeneous crystallization with the development of the front of growing crystals in the direction opposite to heat removal, i.e. perpendicular to the layer formation surface;

– the sprayed coating has pores and an extensive network of boundaries;

– when spraying coatings, there is an intense interaction of the elements included in their composition with the environment and working gases, in particular oxygen, which leads to a significant change in the phase composition and properties of the coatings.

Despite these features, the following could be expected to occur structure changes. As a result of electrical contact processing of sprayed coatings made of flux-cored wires, the formation of modified gradient structures containing a high-strength matrix phase (solid solution of carbon in (–Fe)), as well as inclusions of carbides and austenite, is possible in the surface layers.

In this case, the presence of increased amounts of austenite in the modified layer can help increase the fracture toughness and abrasive resistance of the coating [3, 10-11], and the presence of high-strength phases (martensite and carbides) in the layer should provide increased strength, as well as wear resistance of gas-thermal coatings under conditions of boundary friction and friction without lubrication. In addition, thermal force exposure at elevated temperatures can reduce the porosity of the coating and increase its adhesive resistance.

Metallographic studies showed (Fig. 4) that, as expected, as a result of thermal force exposure, the so-called "healing" of pores occurs, noted in [10, 11], the density of the coatings increased quite noticeably (porosity was 3–5%). Quantitative stereological analysis of porosity was carried out using the Genias 26 program on a certified automatic image analyzer Mini-Magiscan from Joyce Loebl, England ((Fig. 4).

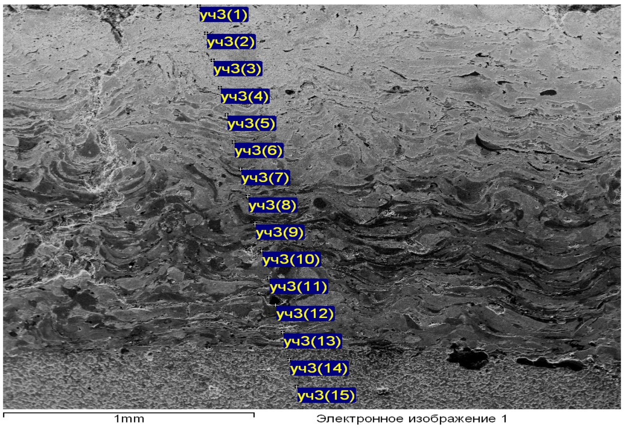


Fig. 4. Structure of the coating obtained by electric arc spraying of powder FMI-2 after electrical contact processing

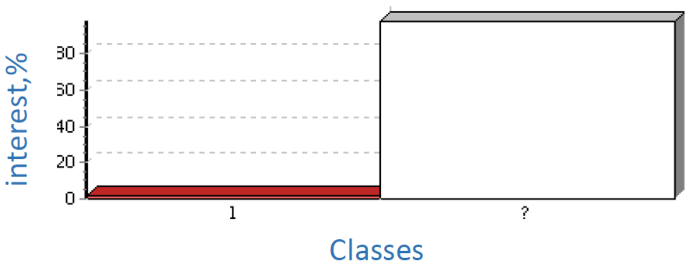
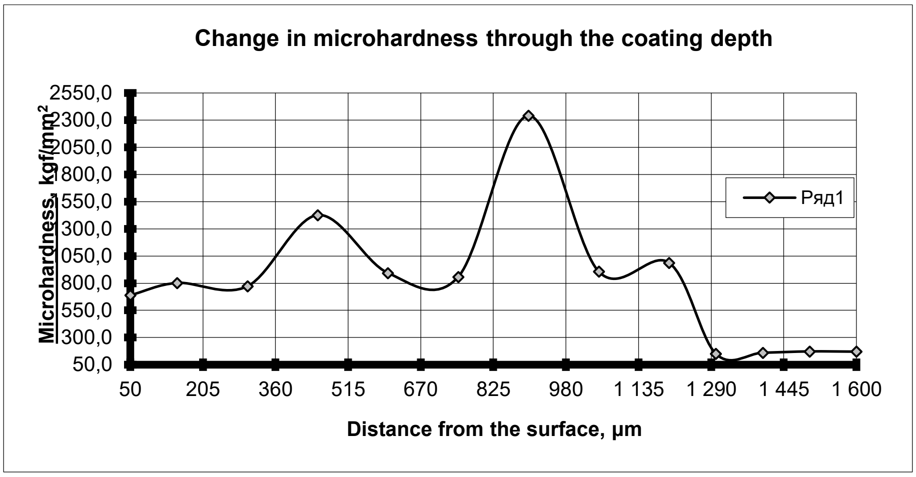
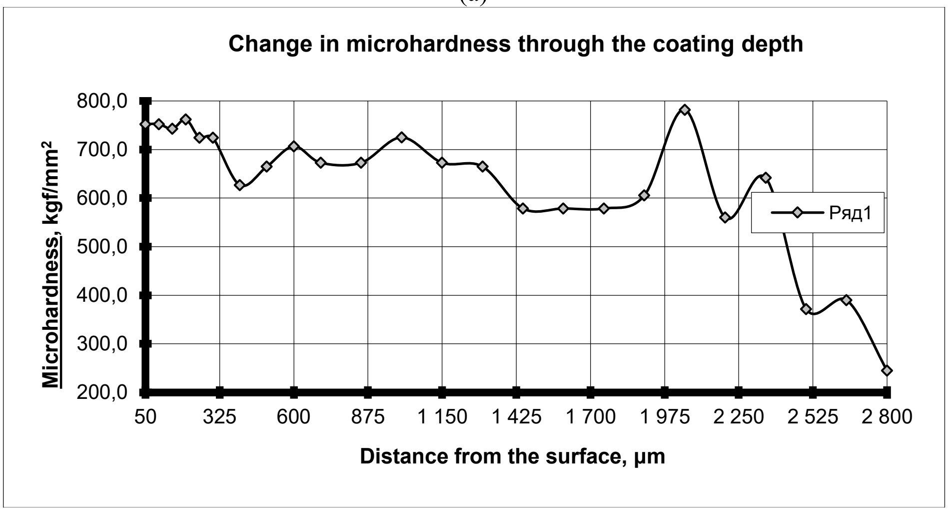


Fig. 5. Results of quantitative stereological analysis of the porosity of the coating obtained by electric arc spraying of powder FMI-2 after electrical contact treatment

Durometric studies have shown that in the process of electrical contact processing there is an increase in the hardness of the surface layer, a decrease in the microhardness of subsurface layers and an increase in microhardness in deeper layers. It has been suggested that the surface layer of the gas-thermal coating is re-hardened. Hardening leads to an increase in microhardness, and high tempering of subsurface layers contributes to their softening. In deeper layers, during electrical contact processing, the decay of retained austenite occurs, accompanied by an increase in microhardness (Fig. 6).



(a)



(b)

Fig. 6. Distribution of microhardness along the depth of sprayed coatings from the edge of the coating surface to the base, including the transition zone: a – sprayed coating made of FMI-2 flux-cored wire; b – sprayed coating of flux-cored wire FMI-2 after electrical contact treatment

Microhardness measurements were carried out using a Micromet-II microhardness tester with a load of 100 g.

Conclusions

Summarizing the results of our own research on the influence of factors of the electric arc spraying process on the structure formation and properties of coatings, and also taking into account the literature data, we established the following parameters of the EDS process during the research:

– current strength – 160...180 A;
– compressed air pressure – 0.5...0.6 MPa;
– spraying distance – 100...130 mm;
– diameter of the wire used – 1.6...2 mm;
– nozzle hole diameter – 7 mm;
– surface preparation method before spraying – shot blasting;
– method of processing sprayed coatings – electric contact.

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Лопата О.В. , Лопата В.М. , Качинська І.Р., Забойкіна Н.П. Вплив факторів електродугового напилення на властивості покриттів

В статті розглянуті первинні (технологічні фактори), які стосуються технології і умов напилення і вторинні, які є похідними від технологічних чинників, що впливають на структуроутворення і властивості покриттів. В роботі досліджено вплив дистанції напилення, дисперсності розпилюємих частинок, матеріалу дроту та ін. на властивості електродугових покриттів. Узагальнюючи результати досліджень по впливу чинників процесу електродугового напилення на структуроутворення та властивості покриттів, були установлені параметри процесу електродугового напилення, вибрані метод підготовки поверхні перед напиленням і. спосіб обробки напилених покриттів.

Ключові слова: електродугове напилення, властивості, структуроутворення, технологічні фактори, покриття, мікротвердість, щільність, зносостійкість, міцність зчеплення