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Technologies and materials for the renovation of erosion-worn parts of automobile equipment

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Abstract

The article presents the results of the development of a technological method and equipment for the renovation of erosion-worn parts of automotive equipment. In the parts of machines and mechanisms subjected to mechanochemical wear, thin-sheet steel, the specific weight of which in car structures is on average 80%, is especially destroyed, as well as the working organs of machines: threaded joints, welding seams, internal friction surfaces (hubs, bearings, rollers and etc.). The solution to this problem is simplified when surface surfacing is used and it is possible to obtain a relatively flat surface with good separation of the slag crust without sharp height differences in the overlapping area.For welding wear-resistant and corrosion-resistant layers, it is necessary to use wires with a diameter of up to 2 mm, which allow applying thin layers of steel alloyed mainly with Cr, Ni, Mn, Mo during arc welding. The welding of such steels to ensure high quality of the deposited layers from the point of view of achieving high corrosion resistance is quite difficult. This is due to the fact that during the operation of welded parts and even when they are kept for a long time before operation, stripes with low corrosion resistance appear on the welded surface (dark colors on the polished surface of the working layer). In the process of developing the technology of surfacing the surface of worn parts, powders of ultra-fine particles were developed, which were used to fill the core of powder-coated wires with diameters of 1,6 and 2,2 mm. The composition of the charge included exotic additives, in particular chromium, molybdenum and complex liquid and alkaline earth ligatures, in particular yttrium and cerium, which made it possible to significantly increase the wear resistance of the deposited layer.

Key words: surfacing, corrosion, wear, modification, alloying, structure.

Introduction

As evidenced by literary sources [1-9,11] and practice, long-term operation of automotive parts in conditions of mechanochemical wear (mechanical friction) is accompanied by local damage (in the form of ulcers), which lead, as a rule, to loss of performance of the unit or device as a whole.

It is possible to reduce the negative impact of local wear and tear on the performance and, in general, the accident-free resource of the main elements of automotive equipment by performing strengthening procedures in relation to the areas of probable wear predicted in advance. Moreover, it is desirable to do this at the stage of manufacturing parts, and even more so during the repair of parts. This problem is equally characteristic of friction gears, variator cups, thrust of control mechanisms, etc.

Thus, in the process of corrosion and mechanochemical wear, a large proportion of nodes that fail prematurely are lost. Thus, according to the data of the source [1] only in Ukraine in 2001, losses from corrosion and wear and tear were estimated annually at approximately more than 2 million tons. At the same time, 1 million tons are irretrievably lost annually. For example, up to 2 million tons of metal is lost in the form of scrap, i.e., unusable products for further operation, which are discarded due to high wear and corrosion of individual units and assemblies, i.e., such a part of assemblies is excluded from the active part and goes to scrap metal.

At the same time, it is known [1] that the costs of repairing nodes per day of work are 4 times higher than the costs of repairing cars and 4.5 times higher than the costs of repairing cars, and the costs of repairing imported cars are 8 times higher 10 times.

Studies have established [1] that the intensity of wear of parts of machines and devices subjected to mechanochemical wear increases by 3-4 times and the long-term (fatigue) strength of metal decreases by 40-50%.

It was established that thin sheet steel, the specific weight of which in the construction of automobiles is on average 80%, is especially destroyed, as well as working organs of machines: threaded connections, welding seams, internal friction surfaces (hubs, bearings, rollers, etc.).

Many years of observations have established that parts made of ordinary low-carbon structural steel: St08kp or St10kp without protection, in the non-working period, are subject to corrosion to a depth of .21 mm in the first year. Moreover, the service life of such parts is reduced by 2 times, and the depth of corrosion pitting increases to 50 μm. Without proper conservation and the application of effective anti-corrosion measures (for example, the use of anti-corrosion coatings), automotive equipment will continue to be subject to an intensive process of corrosion damage with severe technical and economic consequences.

Based on the analysis of literary domestic and foreign sources, it can be concluded that in order to solve the problem of anti-corrosion protection and effective preservation of automotive equipment, all the efforts of engineers of welding technologies and related processes should be directed to solving the following problems:

- the implementation of modern technological processes and innovative materials for the restoration of corrosion-damaged and mechanochemically worn parts, which were developed at the Institute of Electric Welding named after E.O. Paton of the National Academy of Sciences and extensively tested at various enterprises and specialized repair workshops;

- advance application of anti-corrosion protection to parts during their production in the basic (factory) conditions of the production cycle, i.e., in the process of conveyor production of agricultural machinery;

- implementation of modern repair and storage technologies with reliable conservation of automobile machines and mechanisms;

-training of highly qualified specialists in the field of anti-corrosion protection of automotive equipment;

- car manufacturers and repair organizations to actively cooperate with the scientific centers of the National Academy of Sciences of Ukraine;

- to widely introduce advanced materials into production, first of all, high-strength, corrosion-resistant, alloyed steels, metal-plastic and polymer materials, composite metals for surfacing wear-resistant materials, use ultra-dispersed powders as a charge of powder-coated wires of small diameter (1.6-2.2 mm).

It is necessary to bring the cost of anti-corrosion protection of cars up to 20% of its total cost.

As is known from practice, most of the equipment parts are operated in corrosive and aggressive environments. The most famous representatives of such parts are rods and plungers of various hydraulic and mechanical devices (Fig. 1), in particular, loading and unloading equipment: shafts and threaded connections of construction machines and mechanisms.

To increase the service life of such parts, their working surfaces are already protected with galvanic coatings, mainly chrome ones, during manufacture. The thickness of the applied layer is, of course, 5-50 microns. The high hardness of chromium (HB 800-1000) and a low coefficient of friction (for chrome on steel, the coefficient of friction kc = 0.16; for chrome-on-chrome kx = 0.12, to a certain extent characterizes resistance against abrasive and mechanical wear as a result of friction in combination, strong adhesion to the base metal, which determined the wide use of only this type of coating [6].

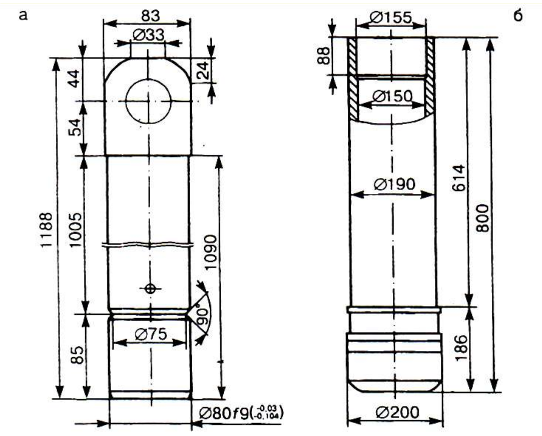

Fig. 1. Rod (a) and plunger (b) of cargo-lifting equipment

One of the methods that allows you to restore worn rods and plungers and friction pairs, as well as to return hydraulic devices and wear nodes to operation is arc surfacing under flux. At the same time, surfacing under the flux of such parts has the following features:

1. Wear of the working surface of these parts is relatively small and is usually within tenths of 1-2 mm. Therefore, surfacing is performed in one layer and powder-coated wires of a relatively small diameter (up to 2 mm) are used;

2. Rods and plungers are mainly made of medium-carbon, low-alloy steels of the type 30ХГСА, 30Х,

which belong to steels with limited weldability. This means that the welding or surfacing of such steels may be accompanied by the formation of cracks. To exclude them, surfacing must be performed using certain technological techniques, in particular, with preheating by applying a soft underlayer;

3. As a result of the mixing of the base and deposited metals during single-layer deposition, it is difficult to obtain the required composition of the deposited metal. To compensate for the effect of mixing, it is necessary to use surfacing materials with a higher degree of doping;

4. On the corroded surface of the parts, areas of chrome coating remain to a greater or lesser extent;

5. Rods and plungers are relatively small in size and weight. At the same time, during their restoration, it is necessary to weld almost the entire outer surface, which leads to overheating of the part and makes it difficult to separate the slag crust. Therefore, it is necessary to apply cooling of the part or interrupt the surfacing process.

Let's consider the technique and technology of welding rods and plungers of hydraulic units. There are two known technologies for surfacing rods and plungers.

The first, the simplest, is surfacing with a low-alloy wire of the 30KhHSA type under the AN-348 flux. Application during cooling of the deposited part with running water allows surfacing along the spiral line of rods and plungers with a diameter of 70-90 mm. The deposited metal in this case is not corrosion-resistant and therefore the deposited surfaces are subjected to chrome plating in the future, as provided by the usual manufacturing technology. The main drawback of the technology is the two-stage recovery scheme with preservation of ecologically polluted production (chroming).

The second technology involves the application for surfacing of corrosion-resistant steels and the exclusion of chrome-plating operations in this connection. The main task in the implementation of this technology is the correct choice of surfacing material. Also, different groups of stainless steels are used in different industries.

The first is martensitic steel. They contain 12-17% Cr and 0.1-0.5% carbon. Hardness cannot reach HPC55.

The second group includes steels of the ferritic class, which contain 16-20% Cr. Their carbon content is usually very low with a low chromium content. With an increase in chromium to 30%, the carbon content can also increase to 0.35%.

As noted above, the considered parts wear out not only as a result of corrosion, but also due to abrasive wear. Therefore, the surfacing of austenitic steels offered by some companies allows to achieve increased corrosion resistance but does not protect the working surface from abrasive wear. For conditions of operation of automotive equipment with increased technological danger, it is most rational to use steels of the martensitic class. However, machining of such steels is difficult due to their increased hardness. The solution to this problem is simplified when, during surfacing, it is possible to obtain a relatively flat surface with good separation of the slag crust without sharp differences in height in the area where the rollers overlap. When considering the influence of chemical elements on the properties of alloy steels, the following can be noted. The minimum chromium content, at which the increased resistance of steel against corrosion in a humid atmosphere and various mildly aggressive solutions is manifested, is approximately 12%. With this chromium content, dense gas-impermeable oxide films are formed on the surface of the metal [2,3,11].

Considering the information presented above from a theoretical point of view, for surfacing wear-resistant and corrosion-resistant layers, it is necessary to use wires with a diameter of up to 2 mm, which make it possible to apply thin layers of steel alloyed mainly with Cr, Ni, Mn, Mo during arc surfacing. However, as the practice of welding such steels has shown, it is quite difficult to ensure the high quality of the deposited layers from the point of view of achieving high corrosion resistance. This is due to the fact that during the operation of welded parts and even when they are kept for a long time before operation, stripes with low corrosion resistance appear on the welded surface (dark colors on the polished surface of the working layer). These strips are located in the overlap zone of the welded rollers.

On the basis of the performed literature review, during the welding of parts such as the rods of hydraulic cylinders, powder-coated wires 30X20MN and 30X22MN were developed and tested, which provide the desired, stainless chromium metal of the martensitic-ferrite class already in the first deposited layer. Based on the fact that metals of type 30X20MN and 30X22MN are characterized by sufficiently high indicators of operational properties, it was decided to bring them to the optimal level by testing during surfacing using various technological methods. In addition, this approach to the selection of the deposited metal was due to the fact that its composition is relatively simple in comparison with the metal 08X20N10G7T recommended for surfacing the cutting edges of mining machines and various devices, which contains an order of magnitude less expensive nickel (with a more than 2 times increased hardness). As can be seen from the composition, the wires contain an increased proportion of chromium to compensate for mixing with the base metal during single-layer surfacing. Since the carbon content in the wire is at the level of the content in the base metal, the composition was not adjusted for carbon.

Development of a new type of powder-coated wire charge type PP-PN-30X20MN with the selection and manufacture of equipment for its production and development of the technology of surfacing with the developed wires

Despite the fact that we proposed two types of flux-cored wires for welding rods - PP-PN-30X20MN and PP-PN-30X22MN, which differ in the content of the alloying element - chromium, which is responsible for the resistance of the deposited metal, the main research was carried out with wire PP- PN-30X20MN, as the most economically favorable.

Arc surfacing under flux was performed in one layer with 30% overlapping of the rollers. The deposited surface was subjected to grinding, as in the previously performed studies.

It is known [2] that a technically effective and economically expedient method of increasing the corrosion resistance of welded metal structures is the microalloying of weld metal with rare-earth, alkaline-earth elements - modifiers. A sharp inhibition of the corrosion process was observed when metal alloying Ce, Y, Ba, Ca. The deposited metal of welding seams, economically modified with micro additives, is characterized by a low content of dissolved gases (oxygen, nitrogen and hydrogen), as well as harmful impurities (sulfur, phosphorus). The low content of gases in the metal containing micro-additives is explained by the high chemical affinity of Ce, Y, Ca and Ba to them, as a result of which thermodynamically strong and almost insoluble in liquid metal oxides, nitrides and hydrides are formed, which are removed into slag during the melting process. that is, the metal is refined.

The positive effect of modifying the deposited metal of type 15X8H2M1 with yttrium in the amount of 0.005-0.013% consists in crushing the primary structure, changing the composition, shape, size and nature of the distribution of non-metallic inclusions, as well as increasing their dispersion. These factors ultimately have a favorable effect on the mechanical properties, wear resistance and heat resistance of the deposited metal. And although the corrosion resistance was not studied in detail in this work, by analogy with the results [1,12] we can assume a positive effect of yttrium on the resistance of the deposited metal to the occurrence of corrosion.

In the experiments, samples made of 40X steel, 40 mm thick (the blanks are similar to those used in the previous experiments) were welded with three flux-cored wires, which differ in micro-additives introduced into the charge:

- sample -1, Al-Ce in the amount of 3% was additionally introduced into the charge of 2.2 mm powder-coated wire;
-sample 2, yttrium in the amount of 3% was additionally injected into the powder wire charge Ǿ2.2mm;
-sample 3, Si-Ca (CK30) in the amount of 3% was additionally introduced into the charge of powder wire Ǿ2.2mm.

The welding mode of all samples I= 250A; U = 30V; V=18m/h; wire protrusion 20-25mm; AN-20P flux.

Preparation of a flux-cored wire charge with components manufactured using ESH

The ability to successfully resist the influence of the environment, in particular corrosive, turns out to be one of the most stringent requirements for modern structural materials, first of all for steels. For stainless steels, the indicated capacity is the main, i.e., the main quality criterion.

The positive effect of electrometallurgical remelting (ESM) on the properties of the deposited metal was shown earlier in experiments using powder wire charge for surfacing tool steel made from a ligature of ESM and ferroalloys [1].

As a remelting component of the charge, we chose the main alloying component - high-carbon ferrochrome FH-800.

In order to fulfill the task, technologies and equipment were used for non-compact material EES without the use of any additional electrodes that support the electroslag process. As a result, a device was produced - a 90 mm current-powered crystallizer, which provides simultaneous performance of three technological functions - support of the electroslag process; rotation of the slag and metal bath and the formation of the remelted ingot. In order to exclude the arc process and increased chromium fumes, the beginning of melting was carried out by pouring molten slag into the crystallizer (liquid start). Melting of the flux and accumulation for its pouring into the crystallizer was performed in a special device (Fig. 2). The process of melting the flux in this device and pouring it into the crystallizer are presented respectively in Fig. 3.

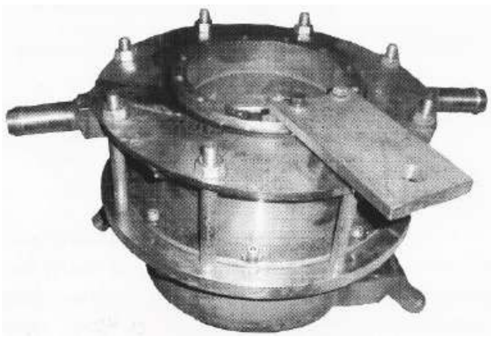

Fig. 2. Current-driven crystallizer Ǿ90 mm

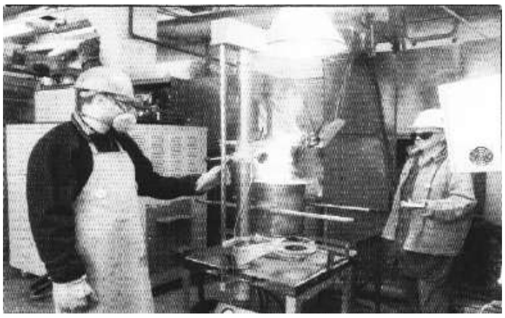

Fig. 3. The process of melting the flux and accumulating slag in the ladle

The ingot obtained as a result of ECP was crushed and dispersed on sieves to obtain powder grains with a size of ≤ 0.3 mm. Later, ferrochrome powder (ligatures) was introduced into the composition of the charge, which was prepared according to the production technology of ordinary powdered wire.

Experiments on arc welding were carried out with experimental flux cored wire on the regimes that were previously taken as a basis.

Production of a charge in the form of ultra-dispersed powder wire particles

The technological method of using ultra-dispersed particles in order to improve the quality of the metal and give it high operational characteristics is based on two scientific representations, the so-called structural heritage in the "charge-molten metal-solid casting" system and the effect of changing the crystallization process of the liquid metal in the presence of a relatively small number of "seed" particles.

The idea of structural inheritance in the charge-molten metal-solid casting system is associated with the dependence of the structure and properties of the casting on the structure and properties of the charge materials observed in practice.

A sensitive modifying effect is provided by the introduction of a small amount of fine-grained (ultradisperse) charge particles into the liquid metal [8]. At the same time, the following processes take place in the liquid metal: the number of inherited particles per unit volume of the melt treated with such particles is much greater than in the untreated melt; the presence of fine-grained particles has an exciting effect on embryogenesis; the dispersed particles themselves turn out to be potential centers of crystallization.

It was assumed that the dispersed component (size < 50 μm) in the charge would be 30% on average. The transformation of a conventional charge into a dispersed charge was carried out in a high-energy device - a planetary mill in a time of 1 hour.

The production of experimental flux-cored wires showed that the presence of a fine-dispersed component in the charge sharply worsens its flow (fluidity) - separate local layers, which differ in color from the rest of the charge, are formed on the dispenser tape of the state of flux-cored wire drawing. Drying of the charge (150oC exposure in the oven for 2 hours and cooling with the oven) does not improve its fluidity.

Therefore, technological techniques used in powder metallurgy and spraying were used - before dosing, the charge was flocculated, followed by sifting of lumps (wiping) on sieves. At the same time, two methods of flocculation were tested. According to the first, the charge is mixed with polyvinyl alcohol, forming a conglomerate after drying. Second, the same process is performed on the KMC glue.

The fluidity of the powder obtained after wiping was evaluated according to DSTU 2640-94 "Metallic powders. Determination of particle sizes by dry sieving". By both methods, it was possible to obtain a charge with satisfactory flowability, which made it possible to produce a suitable powder wire from it with stable arc burning, which ensures high-quality surfacing.

Conclusions

1) The experimental method, which provides for the selection of a relatively low-alloy composition of the deposited metal and the improvement of its properties due to changes in the technology and technique of surfacing, has shown its promise.

2) One-layer surfacing of metal type 30X20MN with any amount of overlap does not allow to achieve high corrosion resistance of the superimposed layer.

3) An increase in the chromium content in the 30X20MN type metal by approximately 2% does not significantly increase the corrosion resistance of the metal due to reaching the lower limit of the chromium content in the remelted metal (base + deposited metal), at which the positive effect of the chromium content in the deposited layer is manifested.

4) Multi-layer deposition improves the corrosion properties of the deposited metal, but its application significantly reduces the cost-effectiveness of the deposition process.

5) By adjusting the surfacing welding cycle, it is possible to improve the corrosion resistance of the

surfacing metal, but this approach complicates surfacing conditions and may have a negative impact on its economic feasibility.

6) It was established that the introduction of RZM into the composition of the charge changes the indicators of metal corrosion in a positive direction.

7) The use of ultradisperse components in the charge of powdered wires should be considered a promising technological method, especially when they are obtained with the help of a binding CMC.

8) The positive effect of ESH on reducing the number and shape of non-metallic inclusions, and, therefore, on the corrosion resistance of the deposited metal obtained by melting powder-coated wire, in the charge of which a ligature was partially used, and not ferroalloys, was confirmed.

9) The use of small current pulses during welding allows you to significantly influence the penetration of the base metal and heat deposition in the metal of worn parts.

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Макаренко В.Д., Максимов С.Ю., Мєшков Ю. Є., Селіверстов І.А. Технології та матеріали з реновації ерозійно-зношених деталей автомобільної техніки

В статті наведені результати розробки технологічного методу та обладнання з реновації ерозійно-зношених деталей автомобільної техніки. В деталях машин і механізмів, піддатих механохімічному зношуванню особливо руйнується тонколистова сталь, питома вага якої в конструкціях автомашин складає в середньому 80%, а також робочі органи машин: різьбові з'єднання, зварювальні шви, внутрішні поверхні тертя (втулки, підшипники, ролики та ін.).

Рішення цієї задачі спрощується, коли застосовується наплавлення поверхні і є можливість отримати відносно рівну поверхню з добрим відокремленням шлакової кірки без різких перепадів висот в зоні перекриття.

Для наплавлення зносостійких і корозійностійких шарів необхідно використовувати дроти діаметром до 2 мм, які дозволяють наносити при дуговому наплавленні тонкі шари сталі, легованої головним чином Cr, Ni, Mn, Mo.

Наплавлення таких сталей, щоб забезпечити високу якість наплавлених шарів з точки зору досягнення високої стійкості проти корозії достатньо складно. Це пов'язано з тим, що під час експлуатації наплавлених деталей і навіть при їх тривалій витримці до експлуатації на проплавленій поверхні появляються смуги з низькою стійкістю проти корозії (темні кольори на шліфованій поверхні робочого шару).

В процесі розробки технології наплавлення поверхні зношених деталей були розроблені порошки з ультрадисперсних частинок, якими наповнювали серцевину порошкових дротів діаметрами 1,6 і 2,2 мм. В склад шихти були введені екзотичні добавки, зокрема хром, молібден та комплексні рідко та лужно-земельні лігатури, зокрема ітрій та церій, що дозволило суттєво підвищити зносостійкість наплавленого шару.

Ключові слова: наплавлення, корозія, зношування, модифікування, легування, структура

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Analysis of the influence of shaker table rigidity on the accuracy of vibration test results for electronic equipment

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Abstract

During vibration tests of structurally complex equipment on electrodynamic shakers, the measured vibrations on the shaker table, test fixtures and various places of the tested product may differ. One of the reasons is the deformable shaker table, the stiffness of which can significantly affect the results of vibration tests. The electronic equipment being tested, as a rule, does not have an axisymmetric shape and therefore, during testing, it is very difficult to align the center of gravity of the product and the vibrating table or equipment with the axis passing through the center of the shaker table. The paper theoretically shows that the shaker table can be considered a rigid body only if there is no displacement of the weight of the tested product from the center of the table, as well as at excitation frequencies significantly lower than the critical frequency of the table. For theoretical analysis, the disc-shaped shaker table is presented in the form of a thin plate. Vibrography of the vibrating platform experimentally confirmed the effect of increasing vibrations when moving away from the center of the shaker table. If during vibration tests it is not possible to place the electronic unit coaxially with the center of the vibrating table, it is necessary to monitor the value of vibrations at different points of the tested product, for example, at the points farthest from the center.

Keywords: vibration test, shaker, test fixtures, electronic equipment

Introduction

Products of electronic equipment used in space and aviation equipment are subject to significant overloads (10…20)g [1]. One of the main parameters of such equipment is their vibration resistance. The specified equipment is subject to increased requirements for vibration protection, since the failure of a relatively inexpensive interconnection, electronic unit or component can lead to the destruction of the entire aircraft [2]. Therefore, during production and operation, on-board electronic equipment is subject to mandatory testing on various types of shakers. Electrodynamic shakers are used for testing electronic devices, assemblies and aircraft units [3, 4]. The accuracy of vibration test results significantly depends on the accuracy of the measured vibration parameters. Idealizing a shaker table or test fixture as an absolutely rigid body increases vibration measurement errors. To improve the quality of vibration tests, it is necessary to take into account the deformability of the vibrating table and equipment.

Literature review

The most important link in the system for ensuring the quality of vibration impacts transmitted to the object during vibration and impact testing of products is the fixture for attaching the test product to the table of an electrodynamic vibration stand [5, 6]. Such fixturte can introduce distortions into the process of vibration transmission from the vibrating table to the product being tested [7]. Vibration monitoring based on readings from sensors installed on the shaker does not reflect real vibrations. Analysis of the results obtained from many vibration tests of electronic control units of aerospace equipment showed a significant spread between the level of vibrations measured on the shaker table and the vibrations of the test fixture or products being tested [8].

When testing electronic equipment, which, as a rule, does not have an axisymmetric shape, it is very difficult to align the center of mass of the product and test fixture with the axis passing through the center of the shaker table. If the axis of the shaker rod and the exciting force acting along this axis do not pass through the center of mass of the product with the table, a bending moment occurs. The associated vibrations of the entire system in planes perpendicular to the plane of the shaker table are superimposed on the main vibrations and further complicate the vibration response. This has prompted many researchers to further investigate vibration transmission models during testing. [9-13].

The authors in [9, 13] created a mathematical model of an electrodynamic shaker, which takes into account the transmit of mechanical load from the launch vehicle to the spacecraft. Possible distortions of the center of gravity of the tested product are taken into account. For this purpose, modal analysis and the design of experiments (DOE) method were used. As a result, three shapes of the shaker head expander were proposed to select the geometry with the best vibration characteristics.

The work [10] shows the principle mechanical and electrical parts of a lumped-parameter, one-dimensional, three DoFs, electromechanical shaker model and describes a basic model of a Modal shaker. It was shown in [11,12] that due to the unbalanced radial electromagnetic force and the displacement of the center of gravity of the tooling or test sample, in practice, an electrodynamic shaker can generate significant vibration in the transverse direction. As a result, the accuracy of vibration control of the equipment under test is greatly reduced. To take into account the lateral vibration of the moving system, a dynamic model of an electrodynamic shaker with 7 DOF was developed in [11].

Purpose

The purpose of this work was a theoretical analysis and experimental study of the influence of the deformability of the VEDS-200 shaker table on the magnitude of the measured vibrations.

Research methodology

Dynamic model of vibrations in the assumption of an absolutely rigid shaker table

Let us consider the process of vibration testing of an electronic product mounted on a shaker, containing a housing and a printed circuit board. In this case, we assume that the shaker table is a rigid body with a mass that much exceeds the mass of the test product. The electronic unit under test, as an oscillatory system, consists of two passive masses, representing its body and board, which are interconnected by elastic elements.

In the general case, the oscillatory system is elastically connected to the movable platform of the shaker. The movement of the moving platform is determined by the kinematic excitation of oscillations of the system under study. Assuming a significant excess of the mass of the moving platform of the vibration stand compared to the masses of the body and board, a discrete model with 2 DOF, which is presented in Fig. 1.

The motion of such a two-mass oscillating system is described by a system of differential equations

$$\begin{cases} m_1\left(\ddot{z}_1-\ddot{z}_0\right)+k_1 z_1+k_2\left(z_1-z_2\right)+c_1\dot{z}_1+c_2\left(\dot{z}_1-\dot{z}_2\right)=0, \\ m_2\left(\ddot{z}_2-\ddot{z}_0\right)+k_2\left(z_2-z_1\right)+c_2\left(\dot{z}_2-\dot{z}_1\right)=0, \end{cases} \quad (1)$$

where m_1 is the mass of the body of the block, represented by a solid body installed on the elastic-dissipative support of the fastening node with a stiffness coefficient k_1 and a vibration resistance coefficient c_1;

m_2 is the mass of the electronic board, whose elastic-dissipative support models the elastic-dissipative properties of the board itself with a stiffness coefficient k_2 and a vibration resistance coefficient c_2;

z_i (i = 1, 2) is displacement of masses m_i;

$z_0=Z_0\sin\omega t$ – is the harmonic oscillations generated by the vibrating platform. The function $z_0(t)$ describes the movement of the moving platform of the shaker, causing the kinematic excitation of the vibrations of the system under study.

The solution of the system of equations (1) has the form:

$$\begin{cases} z_1=U_1\cos\omega t+V_1\sin\omega t, \\ z_2=U_2\cos\omega t+V_2\sin\omega t. \end{cases} \quad (2)$$

After substituting (2) into (1), we obtain a system of four linear algebraic equations for unknowns U_i, V_i (i = 1, 2):

$$\begin{cases} U_1\left(k_1+k_2-m_1\omega^2\right)+V_1\left(\left(c_1+c_2\right)\omega\right)+U_2\left(-k_2\right)+V_2\left(-c_2\omega\right)=-m_1Z_0\omega^2, \\ U_1\left(\left(c_1+c_2\right)\left(-\omega\right)\right)+V_1\left(k_1+k_2-m_1\omega^2\right)+U_2\left(c_2\omega\right)+V_2\left(-k_2\right)=0, \\ U_1\left(-k_2\right)+V_1\left(c_2\omega\right)+U_2\left(k_2-m_2\omega^2\right)+V_2\left(c_2\omega\right)=-m_2Z_0\omega^2, \\ U_1\left(c_2\omega\right)+V_1\left(-k_2\right)+U_2\left(c_2\omega\right)+V_2\left(k_2-m_2\omega^2\right)=0. \end{cases} \tag{3}$$

The amplitudes of mass oscillations m_1 and m_2 are determined by the formulas:

$$Z_1=\sqrt{U_1^2+V_1^2},\ Z_2=\sqrt{U_2^2+V_2^2}\ . \tag{4}$$

Given the statement of the problem, from system (3), using formulas (4) we obtain expressions for determining the relative amplitude of oscillations $\bar{Z}_n=\dfrac{Z_n}{Z_0}$ in particular, for mass m_2, which simulates the concentrated mass of the tested electronic device:

$$\bar{Z}_2=\frac{D_1m_2\omega^2}{D_2}, \tag{5}$$

where

$$\begin{cases} D_1=k_1+k_2-m_1\omega^2+c_1\omega^2+c_2\omega^2, \\ D_2=(k_1+k_2-m_1\omega^2)(k_2-m_2\omega^2)-k_2^2-c_1c_2\omega^2+\omega\left[(c_1+c_2)(k_2-m_2\omega^2)+c_2k_1-c_2(k_2-m_1\omega^2)\right]. \end{cases} \tag{6}$$

In the considered model, the shaker table is presented as a rigid body. However, monitoring vibrations at various places on the shaker table shows that this is not the case, and in fact the table can become deformed [13, 14]. We theoretically study the influence of finite stiffness on the deflections of a shaker table made in the form of a disk.

Mathematical model of a shaker table represented by a flexible thin plate

A typical design of the moving part of an electrodynamic vibration stand is shown in Fig. 2. A vibration table with a thickness *h* and a radius *b* is rigidly bolted to a cylindrical rod with a radius *a*, which performs vertical reciprocating movements at the frequency of the generator of the shaker control system. As a rule, for most vibrating tables the following condition is met $0,025 \le h/a \le 0,2$, therefore, to estimate the rigidity and deflections of the vibrating table, you can use the theory of calculations symmetrical bending of thin circular plates with small deflections [15].

Let us consider an approximate model of a shaker table in the form of an elastic round plate, rigidly clamped along the contour with a radius *r=a* (Fig. 2). The load on the shaker table be distributed uniformly with intensity *q*.

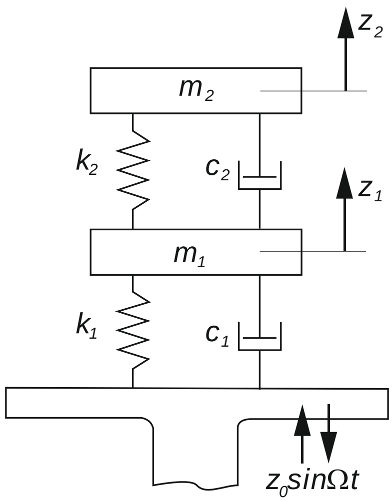


Fig. 1. Dynamic model of oscillations of an electronic product fixed on a rigid shaker table

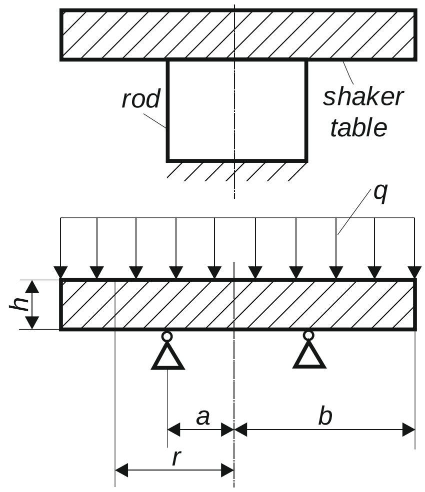


Fig. 2. Load scheme of the deformable shaker table by its own weight

In the polar coordinate system, plate deflection and load are functions of r and θ, respectively: $w(r,\theta)$, $q(r,\theta)$. The differential equation of a curved plate has the form [15]

$$D\left(\frac{d^2}{dr^2}+\frac{1}{r}\cdot\frac{d}{dr}+\frac{1}{r^2}\cdot\frac{d^2}{d\theta^2}\right)\left(\frac{d^2w}{dr^2}+\frac{1}{r}\cdot\frac{dw}{dr}+\frac{1}{r^2}\cdot\frac{d^2w}{d\theta^2}\right)=q\ , \tag{7}$$

where $w=w(r)$ is the deflection as a function of the coordinate r;
q is the uniformly distributed load on the surface;
$D=\dfrac{Eh^3}{12\left(1+\mu^2\right)}$ is the bending stiffness of the plate;
μ is the Poisson's ratio.

The problem is axisymmetric if the load on the plate, as well as the conditions for securing its edges, do not depend on the polar angle θ. Then the deflections do not depend on the polar angle θ, and they are only a function of the coordinate $w=w(r)$. The general differential equation for the equilibrium of the curved middle surface of a circular plate has the form

$$\frac{d^4w}{dr^4}+\frac{2}{r}\cdot\frac{d^3w}{dr^3}+-\frac{1}{r^2}\cdot\frac{d^2w}{dr^2}+\frac{1}{r^3}\cdot\frac{dw}{dr}=\frac{q}{D}\,. \tag{8}$$

Integrating (8), we obtain the equation of the rotation angles

$$w=\frac{qr^4}{64D}+C_1+C_2\ln r+C_3r^2+C_4r^2\ln r\ . \tag{9}$$

The linear radial bending moment is equal to

$$M_r=-D\left(\frac{d^2w}{dr^2}+\frac{\mu}{r}+\frac{dw}{dr}\right)=D\left(\frac{d\varphi}{dr}+\mu\frac{\varphi}{r}\right) \tag{10}$$

where $\varphi=-\dfrac{dw}{dr}$ is the angle between the tangent to the curved middle surface and the axis r.

To determine the integration constants in solution (7), we have the following boundary conditions:

1) $r=a$, $w=0$;
2) $r=a$, $\varphi=0$;
3) $r=b$, $M_r=0$;
4) $r=b$, $Q=\dfrac{dM_r}{dr}=-D\dfrac{d}{dr}\left(\dfrac{d^2w}{dr^2}+\dfrac{\mu}{r}+\dfrac{dw}{dr}\right)=0$;

Substituting the deflection functions into these boundary conditions $w(r)$ (7), moment $M_r(r)$ (8), angle $\varphi(r)$ and reduced shear force $Q(r)$, we obtain the following matrix system of equations:

$$\begin{pmatrix} 1 & \ln a & a^2 & a^2\ln a \\ 0 & a^{-1} & 2a & a\left(1+2\ln a\right) \\ 0 & \dfrac{\mu-1}{b^2} & 2\left(1+\mu\right) & 2\ln b\left(1+\mu\right)+3+\mu \\ 0 & \dfrac{2\left(1-\mu\right)}{b^3} & 0 & 2b^{-13}\left(1+\mu\right) \end{pmatrix}\cdot\begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{pmatrix}=\begin{pmatrix} -\dfrac{qa^4}{64D} \\ -\dfrac{qa^3}{16D} \\ -\dfrac{qb^2}{16D}\left(3+\mu\right) \\ -\dfrac{qb}{8D}\left(3+\mu\right) \end{pmatrix}. \tag{11}$$

Solving system (11) we find the integration constants C_1, C_2, C_3, C_4.

To illustrate the nature of the behavior of dependence (7), an analysis of the obtained results was carried out on the example of the deflection of the shaker table of the laboratory vibration stand VEDS-200, the appearance of which is presented in fig. 3. The technical characteristics of the shaker are given in the table. 1. The characteristics of the shaker table of this vibrating stand are given in the table. 2 To calculate the maximum deflections, we will use the maximum permissible load conditions from the technical specifications. At the same time, the transverse force is uniformly distributed over the surface of the vibrating table with intensity q=11493 Н/м^2.

Table 1.

VEDS-200 Shakers specifications

Maximum of force shaker	Maximum payload	Displacement	Frequency range	Acceleration without load	Acceleration with maximum load
2000 N	45 kg	12,5 mm	5-5000 Hz	40g (392 m/s^2)	4g (39 m/s^2)

Table 2.

Shaker table specifications

Material	Table's Radius	Rod's Radius	Height	Young's modulus	Poisson's ratio
Aluminum	b=230 mm	a=90 mm	h=25 mm	E=70 GPa	μ=0,34

Having solved system (9), we obtain: C_1=-0.0538·10^{-3}, C_2=-0.0172·10^{-3}, C_3=-0.8828·10^{-3}, C_4=-0.9994^{-3}. Analytically calculated according to dependence (7), the shape of the middle surface bend in XYZ coordinates is presented in Fig. 4, where $r = \sqrt{x^2 + y^2}$.

Fig. 3. Shaker VEDS-200 with a test electronic unit

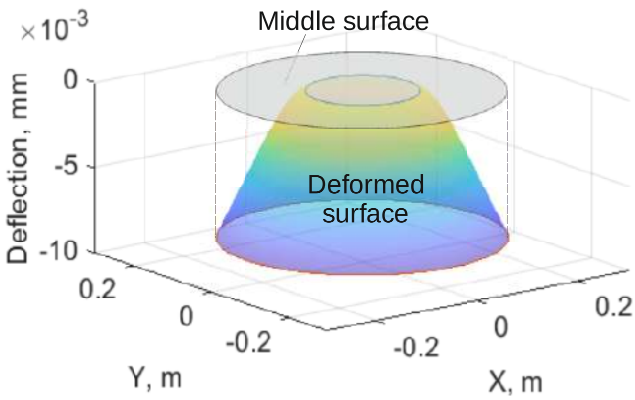


Fig. 4. Static deflection of the shaker table at absence of displacement

The analysis of dependence (7) shows that the rigidity of the shaker table decreases sharply when moving away from point O to the edge of the table. Therefore, when testing large-sized blocks, the attachment of which to the vibrating table is located at a distance $r>a$, the idealization of the shaker table as a rigid solid body in the dynamic model (1) is unjustified. In the model of the testing process, it is necessary to introduce an additional spring with a stiffness of k_3, which takes into account the elastic properties of the shaker table. Such a spring is connected in series with a spring with stiffness k_1, simulating the stiffness of the body of the electronic product. The resulting rigidity of the vibrating table-body system k_{13} is less than k_1:

$$k_{13} = \frac{k_1 k_3}{k_1 + k_3},$$

which explains the phenomenon of a decrease in the real critical speeds of the shaker-product system and an increase in vibrations compared to those expected in the range of operating frequencies of the shaker.

Results of experimental studies and discussion

To experimentally confirm the deformability of the shaker table and assess the influence of elasticity on the level of vibrations at different points on its surface, experimental studies were carried out. The subject of study was the VP-90M platform of the VEDS-200 shaker expansion table in the form of an aluminum plate. Before the study, the platform was divided into 12 sectors.

In each sector at a distance of 100; 330; and 560 mm from the center, the working vibration sensor was alternately fixed (Fig. 5). A control vibration sensor was fixed in the center of the shaker table. Both vibration sensors, complete with the amplification equipment of the shaker, were pre-calibrated for an acceleration of 1g. A vibration sensor of the ABC 027-01 type (Fig. 6) complete with a matching amplifier and a VZ-38 millivoltmeter was used as a reference. Sinusoidal oscillations with an acceleration of 1g were applied to the shaker table. The acceleration values were monitored by a working vibration sensor fixed alternately around a circle with a radius of 100, 330, and 560 mm in each of the 12 sectors of the surface of the vibrating table platform. The study was conducted for 28 frequency values in the frequency range of 5-1000 Hz. Based on the obtained values of vibration overloads, diagrams of the distribution of vibration overload on the surface of the shaker table were constructed. Examples of diagrams for sampling frequencies {100, 300, 450, 650, 800, 1000}Hz are presented in fig. 7.

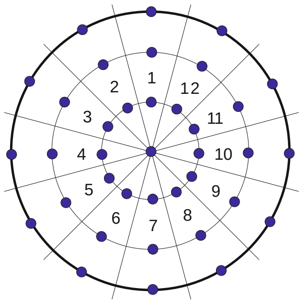
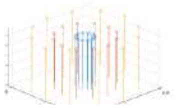
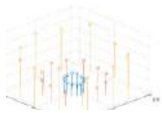


Fig. 5. Scheme of the location of the sensors

Fig. 6. Sensor ABC 027-01

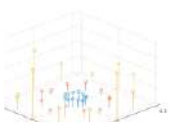


f = 100 Hz

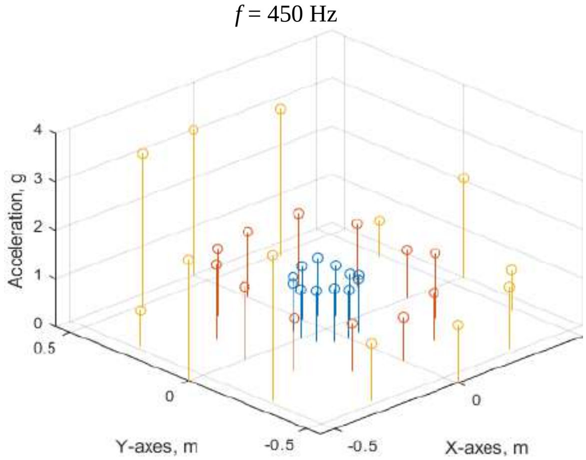


f = 300 Hz

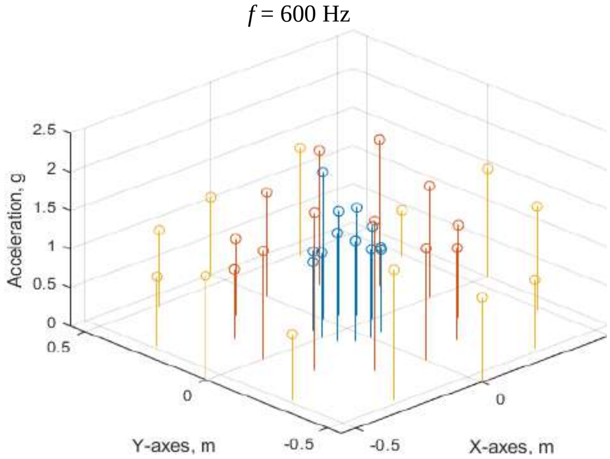
f = 450 Hz



f = 600 Hz



f = 800 Hz



f = 1000 Hz

Fig. 7. Diagrams of distribution of vibration accelerations over the surface of the expansion shaker table at an acceleration value of 1g in the center

Research results show that the values of vibration overloads at different points of the platform of the vibrating table differ significantly from the values measured in the center. They can be from 3 to 6 times less than specified (for example, at f = 450 Hz), or from 7 to 17 times greater (for example, at f = 300 Hz).

Electronic equipment that undergoes vibration tests on electrodynamic vibration stands can have a weight from units to thousands of Newtons. The design of structurally complex electronic devices can be considered as a system consisting of a large number of masses with elastic-damper connections (case, printed circuit boards, components, fasteners, connectors, etc.). Such an electronic unit, having many natural critical frequencies, installed on the vibrating table platform, will further increase the difference in vibration values at the center and other points of the shaker table.

Conclusions

A real shaker table can be considered a rigid body only if the axis of the shaker table rod and the line of action of the exciting force passes through the center of gravity of the test product and test fixture, and also at excitation frequencies significantly lower than the critical frequency of the table. When modeling and simulating electrodynamic shakers, as well as during vibration testing of electronic device structures, it is necessary to take into account the stiffness of the shaker table. Varying the flexibility and deformability of the shaker table makes it possible to more accurately determine the real resonant frequencies of the table testing system. These resonant frequencies are lower than in the case when the shaker table is considered a rigid body. In addition, deformation of the shaker table leads to the fact that the vibrations at different points on its surface are not the same. In practice, this means that when testing an electronic unit, control of the vibration level in the center of the vibration table is inaccurate. Vibrations exceeding the control value can be transmitted from the table to the test fixture and the electronic product being tested, and there they can intensify many times over.

In order to increase the accuracy of test results, it is necessary to comply with the condition that the line of gravity of the device being tested coincides with the axis of the shaker table rod or lies as close as possible to it. In this case, the rigidity of the table is much higher than the rigidity of the product or fastening, and the elastic properties of the table can be neglected.

If during vibration tests it is not possible to place the electronic unit coaxially with the center of the vibrating table, monitoring the vibration value must be carried out at different points of the tested product, for example, at the most distant points from the center.

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Горошко А.В., Зембицька М.В. Аналіз впливу жорсткості вібростола на точність результатів вібраційних тестувань електронних виробів

При вібраційних випробуваннях структурно-складної електронної апаратури на електродинамічних вібростендах виміряні вібрації на столі, оснастці і різних місцях тестованого виробу можуть відрізнятись. Однією з причин є деформівний стіл вібростенда, жорсткість якого може суттєво впливати на результати вібраційних випробувань. Тестоване електронне обладнання як правило не має вісесиметричної форми і тому при випробуваннях дуже складно сумістити центр мас виробу і вібростола або оснастки с віссю, яка проходить через центр вібростола. В роботі теоретично показано, що вібростіл можна вважати жорстким тілом лише за умови відсутності зміщення сили ваги тестованого виробу від центру вібростола, а також на частотах збудження, значно менших за критичну частоту стола. Для теоретичного аналізу вібростіл у формі диску представлено у вигляді тонкої пластини. За допомогою вібрографування вібраційної платформи експериментально підтверджено ефект зростання вібрацій при віддаленні від центру вібростола. Якщо під час вібраційних випробувань немає можливості розмістити електронний блок співвісно з центром вібростола, контроль за значенням вібрацій необхідно обов’язково проводити у різних точках тестованого виробу, наприклад у найвіддаленіших точках від центру.

Ключові слова: вібраційні випробування, вібростенд, оснастка, електронний виріб

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Determination of the dependencies of the wear influence of the cylindrical brush on the operational characteristics of the garbage truck's mounted sweeping equipment

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Abstract

The article is dedicated to the establishment of dependencies of the influence of the wear of the cylindrical brush on the operational characteristics of the mounted sweeping equipment of the garbage truck. By using the planning of the second-order experiment with the first-order interaction effects, using the Box-Wilson method, the adequate dependencies of the influence of the wear of the cylindrical brush on the performance characteristics of the mounted sweeping equipment of the garbage truck were determined. It was established that, according to the Student's criterion, among the investigated factors of influence, the wear of the cylindrical brush has the greatest effect on the deformation of the cylindrical brush, and the width of the contact spot has the least influence. The required pressing force of the cylindrical brush is most affected by the width of the contact spot, and the least by the wear of the cylindrical brush. The response surfaces of the target functions are shown – the amount of deformation and the required pressing force of the cylindrical brush and their two-dimensional cross-sections in the planes of influence parameters, which make it possible to visually illustrate the specified dependences of target function data on individual influence parameters. It was established that the wear of the cylindrical brush of 50% of cases leads to an increase in the deformation of the cylindrical brush by 1.3 times, and the necessary force of pressing of the cylindrical brush – by 3.1...3.6 times, depending on the width of the contact spot. It is shown the expediency of conducting further researches of the effect of antifriction materials on the wear of the friction pairs of the mounted sweeping equipment of the garbage truck.

Keywords: wear, operational characteristics, mounted sweeping equipment, cylindrical brush, deformation, clamping force, garbage truck, regularity, experiment planning.

Introduction

Increasing the wear resistance, reliability and service life of machine parts is one of the main problems that are being solved in the field of mechanical engineering in Ukraine, in particular for sweeping and cleaning machines [1, 2]. To clean the road surface from dirt, the utility machines with brush work equipment are generally used. At the same time, brush work equipment with cylindrical brushes with a pile made of polymer material has become the most widespread. During the work process, the pile of a cylindrical brush wears out when it interacts with the working surface, which contains abrasive particles, while its elastic characteristics change, which requires an increase in the necessary pressing force to maintain the most desirable value of the width of the contact spot under the conditions of ensuring high cleaning quality and minimum intensity of pile wear. According to the analysis of statistical data, the fleet of utility companies of the Khmelnytskyi region experienced a slight decrease in the level of wear and tear in the period 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], an important task is to ensure the use of modern and highly efficient garbage trucks in the country's communal economy. This is important for an industry that is key in the collection, transportation and primary processing of municipal solid waste (MSW). In particular, this is facilitated by the expansion of the garbage truck's functionality by equipping it with attached sweeping equipment. This helps to increase the overall reliability of the functioning of communal enterprises, simultaneously with the solution of various environmental problems. The planning of renewal, maintenance and repair of municipal equipment is facilitated by determining the dependencies of the influence of the wear of the cylindrical brush on the operational characteristics of the mounted sweeping equipment of the garbage truck.

Analysis of recent research and publications

The article [6] sets out measures that allow to significantly increase the efficiency of the technological process of road surface cleaning, reduce the need for cleaning equipment and manual labor costs, and improve the sanitary-hygienic, aesthetic, and transport-operational condition of road surfaces in urban areas. In particular, it is stated that the required modulus of elasticity of road surface of inner-quarter passageways should be at least 125 MPa, sidewalks and pedestrian alleys with a width of more than 3 m – not more than 85 MPa. When the humidity of the garbage is up to 20%, it is advisable to use sweeping machines, additionally moistening the garbage with a humidity of less than 15%, and when the humidity of the garbage is more than 20%, it is advisable to use washing machines.

The work [7] presents the results of a study of a set of partial indicators (operating fuel consumption, performance of work, costs for maintenance and repair of elements of brush work equipment, cost of cleaning a fixed unit of the area of a road or urban area), which can be used to evaluate the effectiveness of the use of communal cleaning machines with a brush working body; the functional scheme of the formation of the generalized efficiency criterion is presented and the mathematical expression for its determination is obtained. An expression for the determination the generalized criterion for the efficiency of the use of utility vehicles is obtained, which is based on the selected aggregation function. Also, for a visual presentation of the interrelationships of factors that affect the partial efficiency indicators of the use of a communal sweeper machine, with a generalized efficiency criterion, a functional scheme of its formation is proposed in the work.

The materials of the article [8] present a study of brush modeling using the finite element method to facilitate the automation of the road sweeping process. Depending on the type of garbage and road conditions, the sweeper machine's driver needs to adjust the vertical pressure, angle of inclination and rotation speed of the curb brush, and also has to frequently monitor the sweeping results. The driver's job becomes more difficult because he has to concentrate on the road and sweep its surface at the same time. Achieving effective road sweeping has been difficult in the past, in part because the basic characteristics of sweeping brushes were unknown. A finite elements model was used to analyze the deformation of metal sweeping brushes when they are compressed and rotated on the road. The following key brush parameters were considered: bristle length, width and thickness, bristle installation radius, bristle installation angle and bristle orientation, number of bristles per cluster, number of clusters per row, and number of rows. The brush bristles were treated as thin cantilever beams and modeled by the commercial FEA software package ANSYS. Using this model, some important brush characteristics such as force-deformation relationship, contact pattern, and torque were obtained. By means of this model, the influence of different geometry of the bristle on the characteristics of the brushes was also analyzed.

In [9], it is stated that brush seals can improve engine performance by reducing losses. Brush seal wear models provide methods for predicting wear and leakage. However, rotor eccentricity, radial deformation, and bristle hysteresis effects are not systematically considered in existing models, which can lead to large errors in some cases. To investigate the effect of rotor-stator eccentricity and radial strain on the wear process and leakage characteristics of a brush seal, a brush seal test was conducted, in which the air leakage rate was measured at different test times and operating conditions, and the eccentricity and radial strain were measured using eddy current sensors. The test results showed that eccentricity and radial deformation significantly affected the wear behavior and leakage efficiency. In the theoretical study, the abrasive wear equation is adopted to describe the loss of material by bristles, and a simplified description is used to express the eccentric movements of the rotor-stator. A wear model of the brush seal was obtained, taking into account the eccentricity of the rotor-stator and radial deformation, in which the hysteresis effect is particularly pronounced. The wear model was validated quantitatively based on brush seal test data, and the results show that there is an error of 20% with the estimated wear loss when rotor eccentricity, radial deformation and hysteresis effect are comprehensively considered.

The idea of the work [10] is to take into account the mutual, force and temperature influence on the friction and wear of the brush pile, as well as to establish quantitative characteristics that determine the resource and efficiency of the sweeping work process in relation to the properties of the removed dirt and the operating modes of the process itself. A simulation model of the functioning of the brush unit of a communal cleaning machine was developed and implemented on a PC, which allows predicting the characteristics of the process and identifying their cause and effect relationships with the parameters of the brush, modes and conditions of the work process itself. The simulation model makes it possible to predict the resource and performance of the brush even at the early stages of designing the brush body of the utility vehicle, and taking into account the model conditions of its subsequent use. Parametric adjustment of the simulation model was carried out by matching the estimated and experimental values of brush pile wear obtained in real conditions. The criteria characterizing the intensity of brush pile wear are also defined. It has been established that the main reason limiting the improvement of the operating modes of utility vehicles is the frequency of rotation of the brush and, to a lesser extent, the speed of the vehicle, the heating of the contact surface of the pile occurs, and, as a result, the intensity of wear increases due to the decrease in the mechanical properties of the material of the pile.

Article [11] is dedicated to the problem of improving the quality of road surface cleaning and increasing the operating life of brush work equipment. Improving the quality of cleaning and the operating life of the brush work equipment will allow to reduce the costs of the utility machine. In the work process, the pile of the cylindrical brush wears out, while its elastic characteristics change, which is reflected in the necessary pressing force to maintain the most favorable value of the width of the contact spot under the condition of ensuring high cleaning quality and minimal intensity of pile wear. The dependence of the degree of pile wear of brush work equipment on the actual radius of the cylindrical brush is given. The effect of the degree of wear on the elastic characteristics of brush work equipment is considered. The dependence of the average stiffness coefficient on the degree of wear of the pile of a cylindrical brush, as well as the value of the required pressing force on the degree of wear for different values of the width of the contact spot of the cylindrical brush, is given. The dependence of the pressure in the hydropneumoaccumulator of the device for controlling the position of the brush working body on the actual free length of the pile wire of the cylindrical brush was obtained.

In the scientific article [12], regression analysis was used to establish dependencies that describe and allow predicting the wear and tear of garbage trucks in Khmelnytskyi region. In addition, the results of this analysis can help develop strategic plans for the infrastructure of utilities, such as the storage and renewal of garbage trucks, the creation of a production base for maintenance and repair. All this is necessary to solve the problem of solid municipal waste management.

The scientific article [13] presents an improved mathematical model of the functioning of the solid waste dehydration mechanism in the garbage truck, which takes into account the wear of the auger. This model made it possible to carry out numerical studies of the dynamics of the mechanism during start-up and to determine the effect of screw wear on the operational characteristics of the device. The results of the study showed that with an increase in the degree of wear of the screw, the pressure of the working fluid at the input of the hydraulic motor of the mechanism increases, and the angular speed and frequency of rotation of the screw decrease significantly with a constant flow of the working fluid. The dependence of these parameters on the degree of wear of the auger was expressed in the form of power functions. In addition, it was established that the wear of the auger by 1000 μm leads to an increase in the energy consumption of the solid waste dehydration process by 11.6%, which, accordingly, increases the costs of this process in the garbage truck and accelerates the process of wear of the auger.

However, as a result of the analysis of known publications, the authors did not find specific mathematical dependencies describing the impact of the wear of the cylindrical brush on the operational characteristics of the mounted sweeping equipment of the garbage truck.

Aims of the article

Study of the effect of wear of the cylindrical brush on the operational characteristics of the mounted sweeping equipment of the garbage truck.

Methods

Determination of the dependencies of the influence of the cylindrical brush wear on the operational characteristics of the mounted sweeping equipment of the garbage truck was carried out by planning a second-order experiment with first-order interaction effects by the Box-Wilson method [14]. The coefficients of the regression equations were determined using the developed computer program "PlanExp", which is protected by a certificate of copyright law for the developed software and is described in the work [15].

Results

Preliminary processing of the results of experimental studies [11] showed that such operational characteristics of the mounted sweeping equipment of the garbage truck, such as the amount of deformation and the necessary pressing force of the cylindrical brush, are functions of the following 2 main parameters:

$$\Delta Y_{CB}, F_{PR} = f(C_w, X_k), \tag{1}$$

where ΔY_{CB} is the amount of deformation of the cylindrical brush, mm; F_{PR} – necessary pressing force of the cylindrical brush, N; C_w – degree of wear of the cylindrical brush , %; X_k – the width of the contact spot, mm.

The study of the influence of the above factors on the amount of deformation and the necessary force of pressing the cylindrical brush when processing the results of one-factor experiments by the method of regression analysis is characterized by the significant difficulties and amount of work. Therefore, in our opinion, it is expedient to conduct a multivariate experiment to obtain regression equations for the response functions – the values of deformation and the necessary pressing force of the cylindrical brush using the planning of a multivariate experiment by the Box-Wilson method [14].

The data about the effect of wear of the cylindrical brush on the value of deformation and the necessary force of pressing the cylindrical brush for different widths of the contact spot are given in table 1 [11].

Table 1

Data on the influence of wear of a cylindrical brush on the amount of deformation and the necessary force of pressing the cylindrical brush for different widths of the contact spot [11]

The degree of wear of the cylindrical brush C_w, %	Width of the contact spot, X_k					
	X_k = 80 mm		X_k = 100 mm		X_k = 120 mm	
	ΔY, mm	F_{PR}, N	ΔY, mm	F_{PR}, N	ΔY, mm	F_{pr}, N
0	2.92	1060	4.58	1426	6.63	1874
10	3.06	1282	4.80	1740	6.94	2312
20	3.21	1572	5.03	2156	7.28	2904
30	3.37	1960	5.29	2722	7.65	3726
40	3.55	2492	5.58	3514	8.07	4907
50	3.75	3242	5.89	4662	8.54	6676
60	3.98	4341	6.25	6399	9.07	9463
70	4.24	6026	6.66	9175	9.67	14157
80	4.53	8767	7,13	13940	10.36	22792
90	4.86	13584	7.66	22953	11,15	40755
100	5.25	23019	8.29	42533	12.08	85554

Based on the data in Table 1, using the planning of the second-order experiment with the first-order interaction effects, by means of the developed software (protected by a copyright law), after rejecting insignificant factors and interaction effects according to the Student's criterion, the dependencies of the influence of the wear of the cylindrical brush on the amount of deformation are determined and the necessary pressing force of the cylindrical brush for different widths of the contact spot:

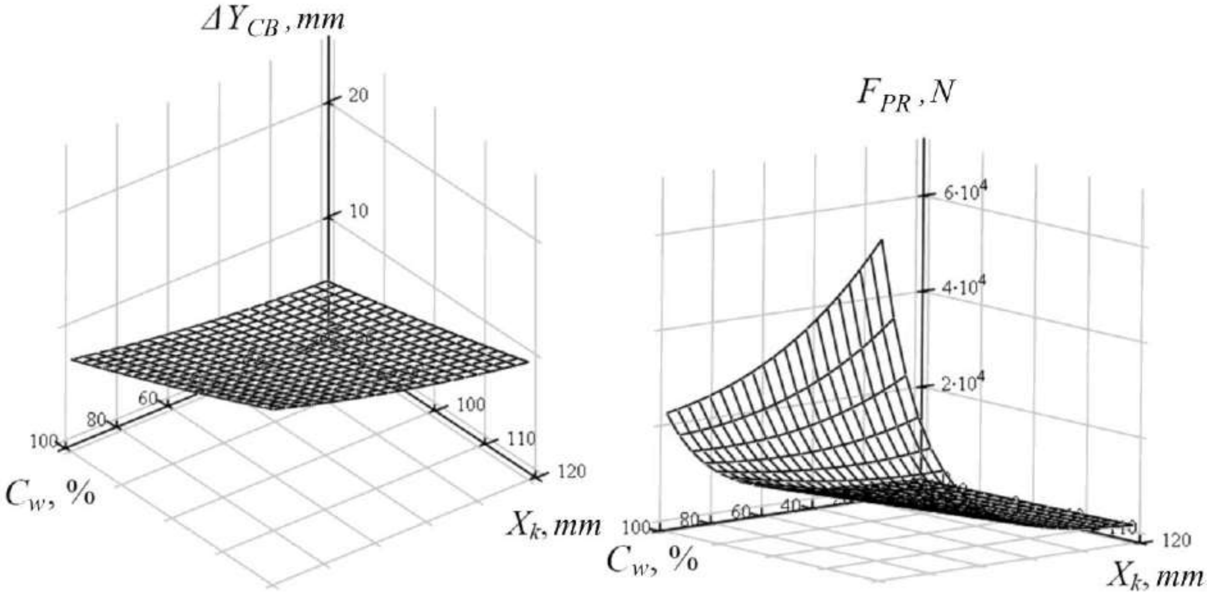
$$\Delta Y_{CB} = 0{,}02832 X_k - 0{,}04836 C_w + 6{,}822\cdot 10^{-4} C_w\, X_k + 1{,}674\cdot 10^{-4} C_w^2 - 4{,}297\cdot 10^{-4} X_k^2\,; \qquad (2)$$

$$\ln F_{PR} = 6{,}13 - 0{,}03422 C_w + 0{,}01138 X_k + 1{,}571\cdot 10^{-4} C_w\, X_k + 2{,}061\cdot 10^{-4} C_w^2 + 3{,}497\cdot 10^{-6} X_k^2\,; \qquad (3)$$

from where, by potentiating the dependence (3), the following is obtained:

$$F_{PR} = e^{6{,}13 - 0{,}03422 C_w + 0{,}01138 X_k + 1{,}571\cdot 10^{-4} C_w\, X_k + 2{,}061\cdot 10^{-4} C_w^2 + 3{,}497\cdot 10^{-6} X_k^2}\,. \qquad (4)$$

In Fig. 1 shows the response surfaces of the objective functions – the amount of deformation and the required pressing force of the cylindrical brush and their two-dimensional cross-sections in the planes of influence parameters, built using laws (2) and (4), which allow to visually illustrate the specified dependencies.



a) **b)**

Fig. 1. The response surfaces of the objective functions – the values of deformation (a) and the required pressing force (b) of the cylindrical brush

It was established that, according to Fisher's criterion, the hypothesis about the adequacy of regression models (2) and (4) can be considered correct with 95% confidence. The multiple correlation coefficients were 0.99894 and 0.99315, respectively, which indicates the high accuracy of the obtained results.

According to the Student's criterion, it was established that among the investigated influencing factors, the degree of wear of the cylindrical brush has the greatest effect on the deformation of the cylindrical brush, and the width of the contact spot has the least influence. For the required pressing force of a cylindrical brush is most affected by the width of the contact spot, and the least by the degree of wear of the cylindrical brush.

It was established that the degree of wear of the cylindrical brush of 50% leads to an increase in the deformation of the cylindrical brush by 1.3 times, and the necessary pressing force of a cylindrical brush 3.1...3.6 times depending on the width of the contact spot.

Thus, the determination of the influence on wear and development of recommendations for the selection of anti-friction materials for the friction pairs of the mounted sweeping equipment of the garbage truck require further researches.

Conclusions

The dependencies that describe the wear influence of the cylindrical brush on the operational characteristics of the mounted sweeping equipment of the garbage truck have been determined, which are adequate according to the Fisher criterion. It was established that, according to the Student's criterion, among the investigated factors of influence, the degree of wear of the cylindrical brush has the greatest effect on the deformation of the cylindrical brush, and the width of the contact spot has the least influence. The required pressing force of the cylindrical brush is most affected by the width of the contact spot, and the least by the degree of wear of the cylindrical brush.

The response surfaces of the objective functions are shown – the values of deformation and the required pressing force of the cylindrical brush and their two-dimensional cross-sections in the planes of influence parameters, which make it possible to visually illustrate the specified dependences of given objective functions on individual influence parameters. It was established that the degree of wear of the cylindrical brush in 50% of cases leads to an increase in the deformation of the cylindrical brush by 1.3 times, and the necessary force of pressing the cylindrical brush by 3.1...3.6 times, depending on the width of the contact spot. Determination of the influence on wear and development of recommendations for the selection of anti-friction materials for the friction pairs of the mounted sweeping equipment of the garbage truck require further research.

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Березюк О.В., Савуляк В.І., Харжевський В.О., Гарбуз Є.С. Визначення закономірностей впливу зносу циліндричної щітки на експлуатаційні характеристики навісного підмітального обладнання сміттєвоза

Стаття присвячена встановленню закономірностей впливу зносу циліндричної щітки на експлуатаційні характеристики навісного підмітального обладнання сміттєвоза. За допомогою використання планування експерименту другого порядку з ефектами взаємодії першого порядку методом Бокса-Уілсона визначено адекватні закономірності впливу зносу циліндричної щітки на експлуатаційні характеристики навісного підмітального обладнання сміттєвоза. Встановлено, що за критерієм Стьюдента серед досліджених факторів впливу найбільше на величину деформації циліндричної щітки впливає ступінь зносу циліндричної щітки, а найменше – ширина плями контакту. На необхідне зусилля притискання циліндричної щітки найбільше впливає ширина плями контакту, а найменше – ступінь зносу циліндричної щітки. Показано поверхні відгуків цільових функцій – величини деформації та необхідного зусилля притискання циліндричної щітки та їхні двомірні перерізи в площинах параметрів впливу, які дозволяють наглядно проілюструвати вказані залежності даних цільових функцій від окремих параметрів впливу. Встановлено, що ступінь зносу циліндричної щітки в 50% призводить до зростання величини деформації циліндричної щітки в 1,3 рази, а необхідного зусилля притискання циліндричної щітки в 3,1...3,6 рази в залежності від ширини плями контакту. Показано доцільність проведення подальших досліджень впливу антифрикційних матеріалів на знос вузлів тертя навісного підмітального обладнання сміттєвоза.

Ключові слова: знос, експлуатаційні характеристики, навісне підмітальне обладнання, циліндрична щітка, деформація, зусилля притискання, сміттєвоз, закономірність, планування експерименту.

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Friction and wear of current-transmitting contact elements of electric transport with the use of metal-graphite composite materials

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Abstract

The work provides an analysis of research devoted to the problem of manufacturing and operation of current-transmitting elements of electric transport, namely, the durability of contact parts according to operational and tribological characteristics. The work of current-transmitting elements of electric transport consists in the continuous sliding of one element on the surface of another and is accompanied by wear. At the same time, two types of wear are distinguished: mechanical and electrical. It has been established that the correct choice of materials has the greatest impact on reducing friction and wear of electrical contact elements. The basis for this is graphite material, which has the best current-conducting characteristics, but has insufficient strength and wear resistance. Approaches to the creation of materials for electrical contact elements using composite metallographite materials based on copper, aluminum, lead and other materials are analyzed.

Key words: electric transport, metal-graphite inserts, friction, wear, composite materials.

Introduction

The work of current-transmitting elements of electric transport consists in the continuous sliding of one element on the surface of another and is accompanied by wear. At the same time, two types of wear are distinguished: mechanical and electrical. Electric current accelerates wear, especially during sparking and arcing. The ratio between electrical and mechanical wear depends on the contact pressure between the transmission contact element and the copper wire.

The main foreign manufacturer of electrical contact elements is the company "Electrokarbon". Electric contact brushes are produced for various international companies, such as BOSCH, Makita, Hitachi, Hilti, etc. Most of these brushes are standardized and differ only slightly in geometric dimensions.

Contact inserts of various designs are used in the trolley bus collector: profile shape, flange, cross-sectional configuration along the length and shape in plan, as well as material: carbon graphite, metal and metal-ceramic. The applicability of one or another type of inserts is determined by their technical characteristics: resistance to abrasion, mechanical strength, electrical conductivity, spark intensity when ensuring the durability of contact wires of trolleybus lines, as well as their cost, which is often decisive. for the consumer. However, despite these structural differences, as well as differences in the use of materials (compositions) in the manufacture of contact inserts, it is possible to single out a common design feature of the inserts.

A carbon brush that slides over an electrical contact carries current from or to the moving surface. The brush performs this function within a limited mechanical system. Unlike most other electrical contacts, brushes require more frequent replacement, resulting in longer brush wear, which is a key issue. Brush wear is caused by a combination of mechanical wear from friction and electrical wear due to excessive surface contact resistance (arcing). For quantification, this leads to frictional breakdown and causes mechanical wear of the brushes and voltage drop is the main indicator of electrical wear. At any time during operation, the carbon brushes wear both mechanically and electrically at the same time. Thus, total wear is the sum of mechanical and electrical wear. It is also important to note that there is often a slower rate of wear with the highest allowable brush pressure.

However, insufficient attention is paid to electric contact elements of trolleybuses in modern literature due to their limited use. At the same time, current-carrying elements of railway transport have a lot in common with trolleybus collectors. At the same time, such constructions are more widely used in the world.

Main material

Among the problems related to the manufacture and operation of current-transmitting elements of electric transport, the main one is the durability of contact parts in terms of operational and tribological characteristics. The study of the wear resistance of electrical contact inserts is carried out by theoretical and experimental methods. Bench and operational tests are necessary to verify the effectiveness of the proposed technological and design recommendations. At the same time, the bench tests should be close to the operating conditions of the friction unit.

In studies [1-2], the authors proposed a device for testing the elements of the contact electrical network of transport for friction and wear (Fig. 1). The device had the following parameters: the maximum speed of rotation of the disk with a contact wire was 1200 rpm; the length of the contact wire, which is installed on the disc, 1 m; pressure 1.5... 8.5N; the current through the sliding contact was 500 A; humidity in the contact zone varied in a controlled manner.

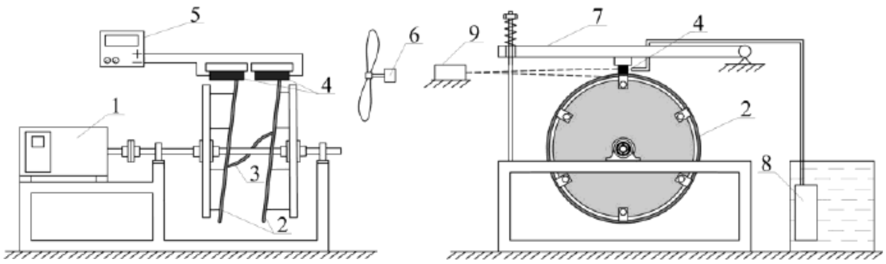

Fig. 1. Device for the study of electric contact pairs of friction [1]:
1) converter, 2) contact wires, 3) connecting conductor, 4) contact bars, 5) power source, 6) cooling system, 7) clamping mechanism, 8) pump, 9) thermometer

To obtain qualitative results of wear of friction pairs, tests were carried out for different types of contact strip materials: graphite, carbonite, copper.

The wear of the contact wire and contact strips was assessedafter 10,000 passes of the contact bars with the contact wire. Each test was performed 6 times. To ensure constant friction and maintain a constant temperature in contact, the device was equipped with an air cooling system with a non-contact temperature gauge.

The resulting test electromechanical wear of the sliding contact had a clearly defined U-shaped character, which is due to the simulation of real operating conditions. The appearance of condensation on the contact wire was caused by increased sparking, and the separation caused a short-term appearance of an electric arc.

The analysis of the obtained dependences showed that for the contact wire and all types of contact strip materials, an increase in wear was observed with an increase in the clamping force and current strength in the contact. It was established that wear in the friction pair increases with increasing humidity and current regardless of pressure. This is due to the appearance of a low-conductivity film in the contact zone, which dramatically changes the nature of the interaction of the friction pair and significantly increases the contact resistance between the contacting surfaces. Thus, the appearance of moisture in the contact negatively affects the degree of wear of the contact bars. This is especially noticeable for direct current. It was also established that when the pressing force was reduced, electrical wear of components prevailed over mechanical wear. This conclusion applies to both the wear of the contact wire and the contact strips.

In the article [3], the classification and causes of the most common carbon damages of the contact surfaces of pantographs operated on the railways of Poland are given. It is noted that in Poland it is possible to use carbon composite impregnated with metal impurities, the metal content of which in carbon contact pads cannot exceed 40% by weight.

The requirement to comply with the main technological characteristics of the material for carbon contact elements is noted. On the other hand, such limitations do not allow the efficient use of such graphite elements at high voltages (more than 10 kV) and alternating current. In this case, increased heating of the contact elements is possible.

To ensure reliable operation, it is necessary to evenly distribute the copper in the volume of the carbon overlay and firmly connect it to the carbon composite. Failure to comply with this technological requirement leads, in addition to overheating, to delamination, as shown in fig. 2. Exfoliation of the material, in this case copper, is visible in the lower part of the cavity of the depicted defect. In this case, a catenary-related cause can be clearly ruled out due to minor mechanical loads on this part of the catenary strip.

Fig. 2. Exfoliation of the material of the contact element [3]

The most common damage to coal contact strips and the identified causes of their occurrence, listed and classified in the article, testify to the need to observe the appropriate parameters of the material and construction at the stage of design, production and proper technical operation. The causes of damage also indicate the need for constant diagnostics of the state of the catenary network using devices for measuring forces and the location of the catenary network relative to the vehicle.

In work [4], a metal-saturated carbon fiber carbon composite (C/C composite) is recommended for the manufacture of contact strips of the pantograph of high-speed electric railway vehicles, as its mechanical bending and impact strength is much higher than that of ordinary graphite impregnated with metal. The authors investigated the wear properties of a C/C composite impregnated with a copper-titanium alloy sliding on a copper disk under the action of an electric current under the action of arc discharges. The tested C/C composite was produced by pressing and sintering laminated carbon fiber sheets. A certain anisotropy in the physical properties of the material, which arises due to the orientation of the lamination of carbon fiber sheets, has been established. The C/C composite was tested for friction in two directions, parallel or perpendicular to the sheet layer. Test results show that the wear rate when sliding in the parallel direction exceeds the rate in the perpendicular direction. This is especially evident in cases where the material is exposed to higher current density and more frequent arc discharges.

In [5], the authors investigated the effects of friction and electrical phenomena, such as arcing and sparking, which regulate the rate of wear of the sliding contact between the contact wire and the collector strip. These two effects are interrelated in a complex way. Conducted research on the wear of collector tape and contact wire using laboratory tests, conducted comparative tests between different combinations of materials. Dependences on basic parameters such as sliding speed, contact force and current strength are established. A procedure is proposed that combines a wear model for the contact between the collector strip and the contact wire with the simulation of the dynamic interaction between the pantograph and the catenary. The adopted wear model is based on the results of the wear pattern and takes into account the effect of electric current based on the results obtained on the laboratory test bench.

The dependence of the electric contact resistance on the contact force between each contact strip of the pantograph and the contact wire of the overhead line was considered, and the corresponding electric current on each of the two collectors of the pantograph was estimated. The values of contact forces and electric current were entered into the wear model and the degree of wear of collector strips and contact wire along the overhead line was calculated, creating an irregular profile of the contact wire.

The proposed procedure is applied to two cases: the first one compares contact wire wear using copper collector strips and graphite collector strips for a DC line. In the second, the consequences of changing the mechanical tension of the contact wire according to the levels of wear are provided.

Composite electrically conductive graphite-filled materials with increased tribological properties are also of interest. In [6], the tribological behavior of metal matrix composites containing graphite particles is considered. A theoretical hypothesis regarding friction and wear is presented; composites in the presence of a thin lubricating film. Experimental results showed that friction and wear rate in metal matrix-graphite particle composites are significantly reduced compared to those in matrix alloys as a result of the introduction of graphite particles. When the graphite content in metal matrix composites exceeds about 20%, the coefficient of friction approaches that of pure graphite and becomes independent of the matrix alloy. Initially, during the sliding of the film, there is no graphite, but it is formed as a result of surface and subsurface deformation, which leads to the transfer of graphite to the tribosurface. A dynamic steady state of the film is established, which is characterized by its friction and rate of wear. The effects of variables such as normal pressure, sliding speed, and composition on steady-state friction and wear rate are discussed. It was established that the presence of graphite particles in the matrix of aluminum alloys increases their resistance to burrs and allows them to work under extreme lubrication without burrs. Copper-graphite and silver-graphite compositions are used in electric brushes and contact strips.

In the article [7], the effect of alloying aluminum with copper (2–4%), silicon (2–4.5%), tin (10–15%), and lead (10–15%) on its wear resistance under steam friction conditions was investigated with copper contact wire.

In practice, it is customary to use cheap electrographic inserts that work without lubricating the contact wire. According to some parameters, these inserts are superior to metal counterparts, but due to fragility and low strength, they fail as a result of impacts. Their service life is limited, and high humidity and sticking wet snow reduce it by one or two orders of magnitude. Metal-ceramic copper-lead-graphite inserts made of 87% copper powder, 9% lead, 4% graphite are more effective: they do not damage the contact wire and are suitable for use due to their wear resistance, but in the case of atmospheric precipitation, the wear of these inserts is 2.2 times greater than that of electrographite . In addition, their use is limited by the high cost of components and manufacturing. The latter is also characteristic of metal inserts made of aluminum-tin alloys with electrographite bushings placed in the middle part of the working track in fig. 3.

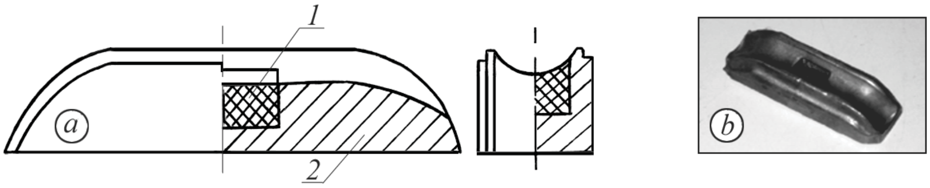

Fig. 3. Combined metal-electrographic current collector insert [7]: (a) structural features, (b) general appearance, (1) electrographite, (2) metal base

With the help of casting, it is possible to achieve high electrical conductivity and lower hardness compared to the contact wire (to prevent its mechanical damage), high wear resistance and low cost of trolley inserts. A comparison of the properties of metallic electrical contact materials shows that aluminum is preferred.

However, even with minor plastic deformations, pure aluminum, compared to other soft metals, tends to stick with copper during dry friction. Under certain conditions, aluminum-based materials capable of self-lubrication (that is, such materials that contain soft but impact-resistant components and a hard matrix).

It has been established that alloying increases the wear resistance of metals and reduces the wear of contact wires. The use of an electrographite sleeve reduces the wear of the metal insert. Field studies of metal trolley current-carrying inserts with electrographite bushings showed that their durability in dry weather is 5-8 times longer, and in rainy weather - 2-3 times longer than that of conventional products.

In [8], the tribotechnical and operational properties of composite materials based on dispersion-strengthened copper were investigated in comparison with the known ones when they are used as current collectors of moving urban transport. The impact on the coefficient of friction and material wear of the method of its compaction - pressing followed by sintering and hot stamping - was studied. It has been established that the highest operational properties have the inserts of tram rails, which are made of material based on dispersion-strengthened copper by the method of hot stamping, which is due to its low coefficient of friction and low intensity of wear of both the material and the counterbody.

High-speed electric sliding was studied in [9] because of its many important industrial applications. In the paper, a friction testing machine with a sliding speed of up to 75 m/s and a current of 100 A was constructed, and the friction and wear resistance of carbon graphite material during high-speed sliding with and without current was investigated. The influence of load, sliding speed and electric current on the tribological behavior of the tested material was investigated. The wear debris was examined by SEM. The test results showed different indicators of friction and wear of the tested material with and without current.

A series of tests on the friction and wear behavior of pure carbon strip/copper AC contact wire was carried out in [10] on a high-speed block slip ring tester. Electric current, normal force, and sliding speed had distinct effects on the test results. The worn spot has the smallest size without an electric current. The worn area increases with increasing electric current. Arc ablation pits, dark arc ablation current lines, skid marks, chips and a copper layer are found on the worn surfaces. The main wear mechanisms are arc erosion, abrasive and adhesive wear.

The service life of the pantograph/contact network system directly affects the stable operation and stable current intake of electric locomotives. In [11], a series of tests was conducted to study the friction and wear behavior of carbon strips and copper contact line using a high-speed line-on-block tester. The friction and wear behavior of carbon strips/copper contact line is significantly affected by normal load, electric currents and sliding speed. By comparing different worn microscopes of carbon strips, it can be found that abrasive wear, adhesive wear and arc ablation are the main wear mechanisms.

In a number of works, the authors focus on the design features of contact electrical systems of transport, both in terms of material composition and the structure of current collector systems.

In [12], the effect of electric current on internal deformation processes in materials is studied. Manufacturing processes (such as forging, rolling, extrusion, and forming) use heat to reduce the forces involved in making parts. However, due to the negative consequences associated with hot processing, it is desirable to use another, more efficient way of applying energy. This article investigates changes in material properties of various metals (aluminum, copper, iron, and titanium-based alloys) in response to the flow of electricity. The theory of electromigration and electroplasticity is reviewed and implications are analyzed. It is shown that with the help of an electric current, the voltages of the currents are reduced, which leads to a lower specific strain energy. The approaches proposed in the work can be used to explain the mechanism of the effect of electric current on materials used in contact transport electrical networks.

The article [13] describes the technology for obtaining a carbon-aluminum alloy of the composite type using a non-autoclaved (gasless) method of impregnating a carbographite base from a matrix aluminum alloy. The use of aluminum alloy as a matrix alloy and carbon graphite or ceramics as a porous blank allows to obtain composite materials that are widely used in mechanical engineering for the manufacture of current receivers, pantograph inserts, electric brushes, sealants, and bearing liners. There are several types of brushes, such as: metal graphite, electro graphite, graphite, connected with resin, carbon graphite. Metal graphite (with impregnation) brushes are used in more responsible nodes and various mechanisms. From this it follows that the use of brushes made of a composite carbon-aluminum alloy will be appropriate and appropriate.

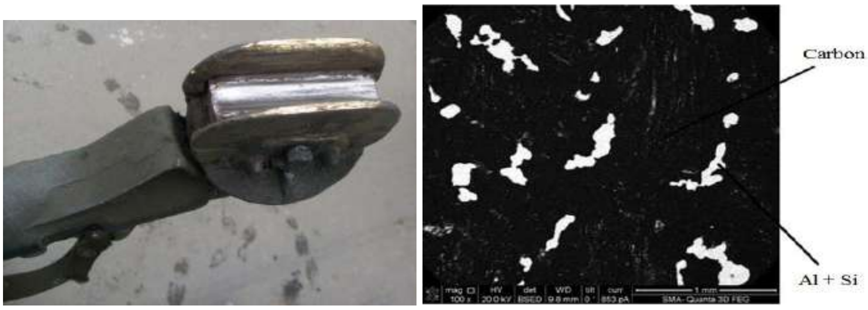

Fig. 4. Carbon graphite inserts of a trolleybus pantograph impregnated with an aluminum alloy [13]

It is advisable to improve the design of contact brushes by impregnating the working layer with an aluminum alloy to increase strength, electrical conductivity and anti-friction properties. In terms of electrical properties, aluminum is not significantly inferior to copper, since its share in the composition of the composite is only 15%, and therefore it has better casting properties (fig. 4). In addition, the use of the gasless impregnation method allows to significantly reduce the cost of composite materials due to the use of conventional structural materials in the equipment. Due to the low cost of equipment, it is possible to manufacture a large number of impregnation tanks for the organization of series or mass production of composites.

The paper [14] considers the problems of extending the life of contact bars for pantographs of electric traction vehicles by choosing the elemental composition of the inserts. In particular, the use of nanostructured crystals of partially stabilized zirconium dioxide for the modification of inserts is proposed. The effect of doping zirconium dioxide crystals with rare earth elements on tribological properties was experimentally investigated. Sample hardness and crack resistance were assessed by the kinetic microindentation method. It has been established that alloying zirconium dioxide crystals is an effective method of increasing strength properties. Samples of crystals that showed the highest characteristics of crack resistance and hardness were selected. Tribological tests of the selected samples under dry sliding conditions were carried out on laboratory friction machines. It was established that the rate of wear of surfaces for constant friction is directly proportional to the nominal pressure. The morphology and mechanism of wear of the friction surfaces were studied, the appearance of unevenly distributed films of secondary structures on the friction surface was shown. The use of zirconium inserts in the contact strips increases the wear resistance and permissible load on the assembled pantograph, which reduces the potential of arc discharge.

The study [15] describes the designs of current collectors, which ensure the prevention of rebound and premature wear of the contact wire on the supports by reducing the lifting resistance of the current collectors. Suspended contact systems for electric vehicles use a catenary or single-contact wire suspended from consoles, brackets, or running wires. For a single contact wire, the inclined pendulum suspension provides optimum performance for pantograph or trolley pantographs, although it is underused in the United States. A typical suspension for a single contact wire consists of straight suspension suspensions with stable arms. A rigid mount has been shown to result in a heavy, stiff suspension, resulting in pantograph bounce, arcing, and premature contact wire wear. Inclined pendulums can be used in constant tension systems or variable tension systems where they provide semi-constant line tension and keep the wire tension relatively constant over a range of temperatures. Such suspensions provide less resistance to the lifting of current collectors at the suspension point, so that the lifting of the contact wire occurs as the collector approaches and passes under it. The energy wave created in the wire by the moving collector allows the collector to pass smoothly without rebound or loss of continuous contact.

The article [16] provides data on particle shape, component and granular composition, for information on the relationship between compact density and pressing pressure for powder materials with special properties based on tungsten and carbon suspensions.

It was shown in [17] that in the manufacture of electrodes and current receivers based on graphite, there is a significant simplification when using a flexible graphite sheet. The incorporation of the flexible graphite sheet Grafoil and its powder into lithium was evaluated using an electrochemical charge-discharge cycle in a configuration with a lithium anode and a graphite cathode. A sheet form with and without a copper current collector was used. It is noted that the relatively low capacity of the Grafoil sheet is explained by the limitation of diffusion of the structure, especially for the high capacity of its powder form. The highly irreversible ability of the powder material may be due to non-functional graphite structures or impurities present in the powder. The presence of the second impedance arc indicates that a structural modification occurs in the graphite anode due to the formation of a porous structure as a result of graphite expansion.

The purpose of the work [18] is to determine the main ways of increasing the resource of inserts of coal current receivers of high-speed electric rolling stock. The existing approaches to the production of surface inserts of current collectors in Europe and Ukraine are considered. The most effective ways of increasing the current-conducting capacity and wear resistance of the elements of the current receiver have been determined. It has been established that the existing system for determining the quality of manufacturing of current-carrying elements has a number of shortcomings that complicate the control of receipt and make it impossible to diagnose current-carrying elements in operation. Based on the facts, we offer a new stand for the needs of the locomotive depot, which will avoid the existing difficulties with the diagnosis of the current collector elements. According to the results of the operational studies conducted on the basis of the locomotive depot, it is proposed to introduce a system of operational diagnostics of the state of the current collector elements during operation. In the course of a comparative analysis of existing and prospective directions of development of current-receiving elements with high load current-conducting capacity and durability, the design conditions for the optimal ratio of inserts were determined. It has been established that a significant part of failures occurs due to an imperfect maintenance system. The obtained results of the analysis of the sources of information determine the need to introduce a copper component to the coal inserts, which will increase the load capacity of the current receivers. Deficiencies of the existing diagnostic systems of carbon current-carrying inserts of pantograph runners have been established, the solution of which should be the basis for the development of new diagnostic tools and systems of current-carrying elements.

In the article [19], a simulation model of the dynamic interaction between the contact network and the pantograph was developed using flexible multibody methods of dynamic analysis. In the analysis model, the pantograph is modeled as a rigid body, and the catenary wire is designed using the formulation of absolute nodal coordinates, which allows efficient analysis of large deformable parts. Furthermore, to represent the dynamic interaction between these parts, their relative motions are constrained by a sliding joint. Using this model, data on contact force and contact loss for a given speed of movement are obtained. The results are evaluated according to the international standard EN 50318.

The purpose of the work [20] is to manufacture hybrid metal matrix composites for dry sliding and to study the effect of sliding speed, load and reinforcement (aluminum oxide and graphite) on wear properties, as well as its contact friction. The behavior of dry sliding during wear of the Al-Si10Mg alloy reinforced with 3, 6, and 9 wt% was considered. of aluminum oxide together with 3% by mass. graphite The method of casting with mixing was used for the manufacture of composites. Mechanical properties such as hardness and tensile strength were evaluated. A disc wear test device was used to evaluate the wear rate and the friction coefficient by changing the loads of 20, 30 and 40 N, sliding speeds of 1.5 m/s, 2.5 m/s and 3.5 m/s. It was found that the mechanical properties of the hybrid metal matrix composites showed significant improvement. The wear rate and coefficient of friction for the alloy and composites decreased with increasing sliding speed and increased with increasing applied load.

In [21], a study of the interaction of contact elements of pantographs of electric transport operated on direct and alternating current sections of railways was carried out. In contrast to the known methods of bench tests, the mechanism of current collection and wear resistance was investigated on a new test setup in a minimally narrow zone of sliding contact. Experimental studies have confirmed that the intensity of wear of contact elements of current collectors depends on the current load of the contact zone, the amount of contact pressure, the area of the contacting surface and the speed of movement. The possibility of maintaining a reliable contact connection in a sliding contact in extreme operating modes in the case of using a reliable contact material of the current collector pads has been practically proven. It is proposed to use a composition of powders based on bronze, iron and graphite for the manufacture of contact elements of current collectors, which can provide reliable contact through interaction with the contact wire.

Conclusions

1. The main problem related to the manufacture and operation of current-transmitting elements of electric transport is the durability of contact parts according to operational and tribological characteristics. The study of the wear resistance of electrical contact inserts is carried out by theoretical and experimental methods. The work of current-transmitting elements of electric transport consists in the continuous sliding of one element on the surface of another and is accompanied by wear. At the same time, two types of wear are distinguished: mechanical and electrical.

2. The correct choice of materials has the greatest impact on reducing friction and wear of electrical contact elements. The basis for this is graphite material, which has the best current-conducting characteristics, but has insufficient strength and wear resistance.

3. The basic approach in the creation of materials for electrical contact elements is the use of composite metallographite materials in a certain ratio of components. Copper, aluminum, lead and other materials with good electrical conductivity and anti-friction properties are used as metal components.

4. It is possible to improve the operational and tribological properties by reducing the contact pressure or its uniform distribution over the contact zone by using the appropriate modernized designs of electric transport current receivers and using computer modeling methods.

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Ковтун О.С., Диха О.В. Тертя та зношування струмопередавальних елементів електротранспорту із застосуванням металографітових композиційних матеріалів

В роботі наведений аналіз досліджень, присвячних проблемі, що стосуються виготовлення та експлуатації струмопередавальних елементів електротранспорту, а саме довговічності контактних деталей за експлуатаційними і трибологічними характеристиками. Робота струмопередавальних елементів електротранспорту полягає в безперервному ковзанні одного елемента по поверхні іншого і супроводжується зносом. При цьому розрізняють два види зносу: механічний і електричний. Встановлено, що на зниження тертя і зносу електроконтактних елементів найбільший вплив має правильний вибір матеріалів. За основу при цьому приймається графітовий матеріал, який має найкращі струмопровідні характеристики, але має недостатню міцність і зносотійкість. Проаналізовано підходи щодо створення матеріалів електроконтактних елементів із застосування композиційних металографітних матеріалів на основі міді, алюмінію, свинцю та інших матеріалів.

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Ключові слова: електротранспорт, метало-графітні вставки, тертя, зношування, композиційні матеріали

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Multicriteria optimization of heat-resistant coatings detonation spraying technology

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Abstract

The paper presents the multi-criteria optimization results of heat-resistant coatings detonation spraying technology. The following criteria for optimization of detonation spraying technology are chosen: critical deformation of coating fracture, adhesion-cohesion equal strength of coating and specific technological cost of coating application. Dependences of the strength properties values of the studied detonation coatings at change of technological and constructive factors have been obtained. It is proved that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the material composition of the sprayed coating, which is caused by the difference in their thermophysical, chemical and mechanical properties, as well as by the physical and chemical processes occurring during the formation of the sprayed layer. The optimum technological parameters allowing to obtain coatings with specified mechanical properties have been established.

Key words: detonation spraying, heat-resistant coatings, multicriteria optimization, structural and technological factors, mechanical properties of coatings.

Introduction

The choice of optimal coatings and technologies for their production is complicated [1, 2]. This is largely due to the fact that the composition and structure of the coating thickness, as well as its thickness, optimal in terms of adhesion properties and durability depend on many factors.

The development of any coating technology is inevitably associated with the solution of optimization problems. This should be explained by the large number of coating application methods in combination with different materials from which the coatings are formed, as well as a large number of influencing factors provides technologies with a wide range of alternative solutions [3]. This has contributed to the development of a new direction – technological processes of protective coatings application optimization according to the criteria of durability.

The peculiarity of the new direction lies in the ideology of conducting research according to a single experiment planning matrix taking into account design and technological factors, a complex of mechanical and operational characteristics. Thus, were optimized according to the complex criterion of fatigue resistance strength, wear and corrosion resistance (gas-thermal coating technologies), adhesion-cohesion equal strength and critical deformation of the base (detonation spraying technologies), isothermal and thermocyclic creep (technologies of electron-beam application of heat protective coatings), strength, stress-deformed state and wear resistance (electrochemical technologies, electrospark alloying) [4].

The work [5] shows the indisputable advantages of detonation coatings, which ensured their widespread use in the world practice of aircraft engine building, as well as in other branches of mechanical engineering.

Literature review

Detonation coating technologies are becoming more and more widespread in industry, including gas turbine construction, and are used both in manufacturing and repair [5, 6]. Detonation spraying technologies are constantly being improved, industrial complexes of modern automated equipment are being developed, mathematical models of this method and optimization approaches have been obtained [4, 7]. Ukrainian scientists have made a great contribution to the development of detonation spraying technology [8]. The V.N. Bakul Institute of Superhard Materials of the National Academy of Sciences of Ukraine has developed the Perun-C unit, the peculiarity of which is the presence of a device for coating and abrasive treatment of the sprayed surface.

At the same time, the efficiency of this technology is hampered by the difficulties in optimizing its modes due to the lack of qualified scientific analysis of research results. Multicriteria optimization of spraying modes will ensure its wider use in all industries.

Let us consider the factors (criteria) that can be used in the multi-criteria optimization of detonation spraying technology of protective coatings.

Parts with heat-resistant coatings characterized by high indicators of wear and corrosion resistance can malfunction due to their delamination (insufficient adhesion of the coating with the part) and cracking of coatings (low cohesion of the coating itself) under the influence of operational loads. It is noted in work [9] that the main criterion that determines the strength of the coating adhesion with the base is the critical deformation of coating fracture (ε_r).

In the practice of creating protective coatings prevails the desire to provide higher adhesion strength of the composition "base – coating" is the main condition for its functionality. Adhesion strength of the system "base – coating" is provided by the technology of coating spraying (temperature of spraying process, jet speed, powder fraction, required quality of the sprayed surface pre-treatment) and selected finishing treatment. It is the coating technology that influences the adhesion strength of the "coating – base" system and has a decisive effect on the load-bearing capacity of the base material. However, by hardening the part by applying a coating, we can get the opposite effect – to unstrengthen it. In order to create an equal-strength composition with minimal de-strengthening, the criterion of adhesion and cohesive strength was chosen in work [10]. This criterion allows to provide simultaneously the necessary indicators of adhesion and cohesive strength of the system "coating – base", and, thus, to exclude delamination and cracking of coatings with minimal de-strengthening of the hardened or restored part material.

The cost of coated parts and the economic effect from the use of detonation coatings depend on a number of factors: type of production, equipment used, materials, part configuration, required dimensional accuracy, etc.

The authors [11] propose to assess the economic efficiency and feasibility of using detonation coatings for restoration and hardening of parts by the criterion of specific technological cost of coating application (C_T):

$$C_T = \frac{C}{S \cdot h}, \tag{1}$$

where $C = C' \cdot K_S$ – cost of coating thickness *h* and area *S*, due to the consumption of powders and gases; $C' = V_f C_f + V_o C_o + V_i C_i + m_p C_p$ – cost per shot; C_f, C_o, C_i – respectively, the unit volume costs of fuel, oxidizer and inert gas; C_p – cost per unit mass of powder; V_f, V_o, V_i – volumes of fuel, oxidizer, inert gas per shot; $K_S = \frac{S \cdot h \cdot \gamma_c}{m_p \cdot K_{mu}}$ – number of shots; m_p – powder weight per cycle; γ_c – coating density; K_{mu} – material utilization rate.

Thus, the following criteria were selected for multi-criteria optimization of detonation spraying technology:
- critical fracture deformation of the coating (ε_r);
- adhesion-cohesion equal strength;
- specific technological cost of coating application due to the consumption of powders and gases (C_T).

Purpose

The aim of the work is the selection of optimal modes of detonation coatings application taking into account technological and constructive factors, providing the obtaining of protective coatings with the required mechanical properties.

Research Methodology

Taking into account the above arguments, a multicriteria optimization of the detonation spraying technology of heat-resistant coatings applied to the parts of tribocouplings of the aviation gas turbine engine hot path has been carried out in the paper, taking into account such criteria as critical deformation of coating fracture, technological cost of the process and adhesion-cohesion equal strength.

According to the estimates of various researchers, the properties of detonation coatings are influenced by 20 to 150 factors [4, 5]. The selection of the most significant factors, on the one hand, should have a dominant influence on the coating properties (optimization parameters), and, on the other hand, should allow their control by the operator. Applying the methods of expert evaluation, using the results of a number of researchers works on optimization of detonation spraying process [6, 9, 12], as well as in order to clarify the specific technological cost of coating application, we selected technological and design parameters for optimization of detonation spraying technology (Fig. 1).

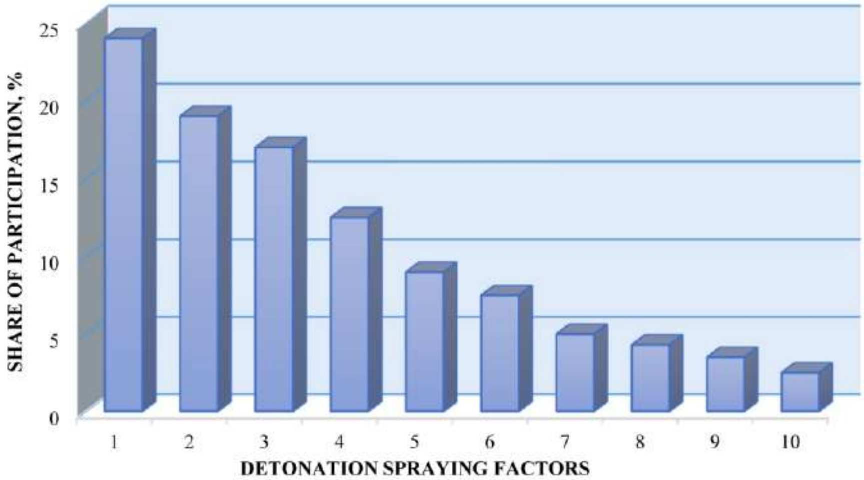


Fig. 1. Ranked series of detonation spraying factors: technological parameters (1 – powder material; 2 – base material; 3 – powder weight per cycle; 4 – spraying distance; 5 – volume of detonating mixture; 6 – number of shots per second; 7 – temperature of water for barrel cooling; 8 – speed of part movement), constructive parameters (9 – coating thickness; 10 – powder granulation).

For modeling the detonation spraying process, based on the analysis of the technological and design parameters presented in Fig. 1, the input parameters that have the greatest influence on the properties of coatings (the value of optimization parameters) were selected. A similar methodology was used in works [13-15].

Table 1 presents the input parameters of the detonation spraying technology (coating material, base material, coating thickness, powder weight per cycle, spraying distance, cost per cycle) that were included in the planning matrix for the optimization of this technology.

Table 1

Levels of design and technological factors variation of detonation spraying technology

Name and designation of the factor	Factor No.	Levels in natural units	Matrix level designation	Levels		
				F_i	X_i	Z_i
Base material, *M*	1	VT-20	VT	0	-1	0,5
		EP-648	EP6	1	0	-1
		EP-718	EP7	2	1	0,5
Coating material, *C*	2	VK-25M	VK	0	-1	0,5
		PG10N01	PG	1	0	-1
		PS12NVK-01	PS	2	1	0,5
Spraying distance, *L*, mm	3	130	130	0	-1	0,5
		170	170	1	0	-1
		210	210	2	1	0,5
Powder weight per cycle, m_p, mg	4	150	150	0	-1	0,5
		225	225	1	0	-1
		300	300	2	1	0,5
Coating thickness, *h*, µm	5	150	150	0	-1	0,5
		250	250	1	0	-1
		350	350	2	1	0,5

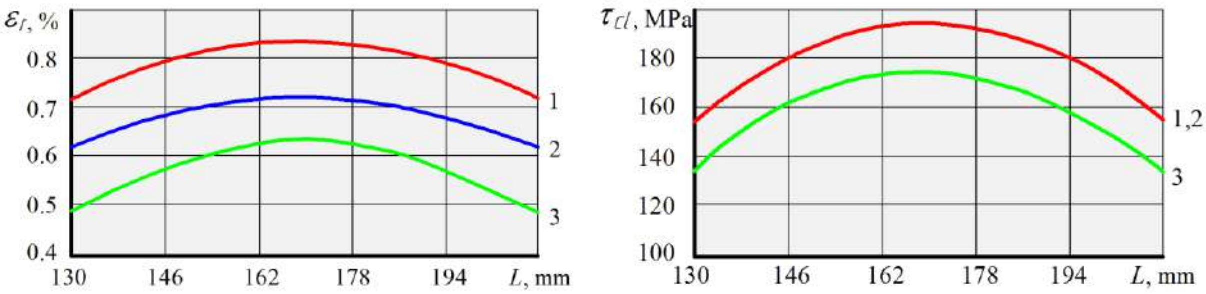
Such powder materials as titanium alloy VT-20, alloys EP-648 and EP-718, which are most often used in the manufacture of tribocouplings parts of the aviation gas turbine engine hot path, were chosen as the base material for research.

Standard powders VK-25M, PG10N01 and PS12NVK-01 were used as materials of heat-resistant coatings. The feasibility of their use for application of coatings by detonation spraying was confirmed in work [12] for hardening of heavily loaded tool materials.

Results

As a result of experimental studies, the strength properties values of the studied detonation coatings at changing technological and constructive factors according to the experiment plan were obtained (Table 1).

Experimental dependences of strength characteristics on spraying distance are shown in Fig. 2 – 5.

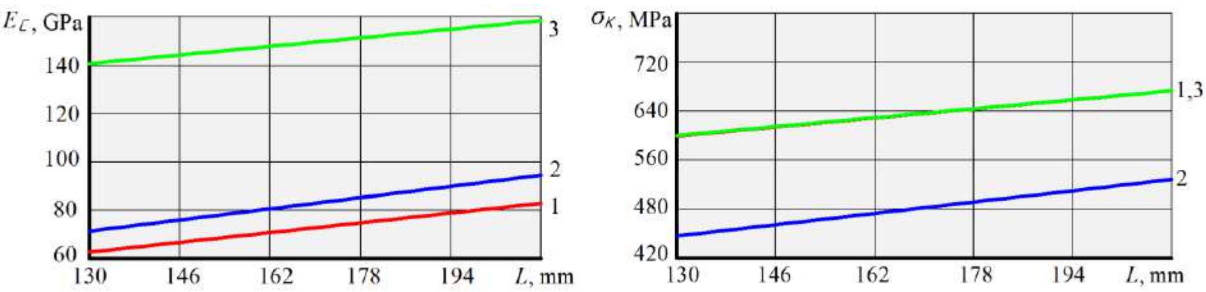


a) b)

Fig. 2. Dependence of critical coating fracture deformation ε_r (a) and shear bond strength τ_{cl} (b) on spraying distance L: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

As a result of the research it was found that ε_r of the base material hardened by detonation spraying has a minimum value (Fig. 2, a), and τ_{cl}, sprayed coating with the base reaches the maximum value (Fig. 2, b) at L = 170 mm.

It has been established that high τ_{cl} of the coatings obtained by detonation spraying with the base is achieved due to not only adhesion bonds at the interface "base – coating", but also chemical ones. This was confirmed by the study of the chemical composition of the transition zone between the coating of powder alloy VK-25M and titanium substrate. Double chemical compounds of cobalt and titanium and triple compounds of tungsten, cobalt and titanium are formed at the interface "powder alloy VK-25M – titanium substrate".

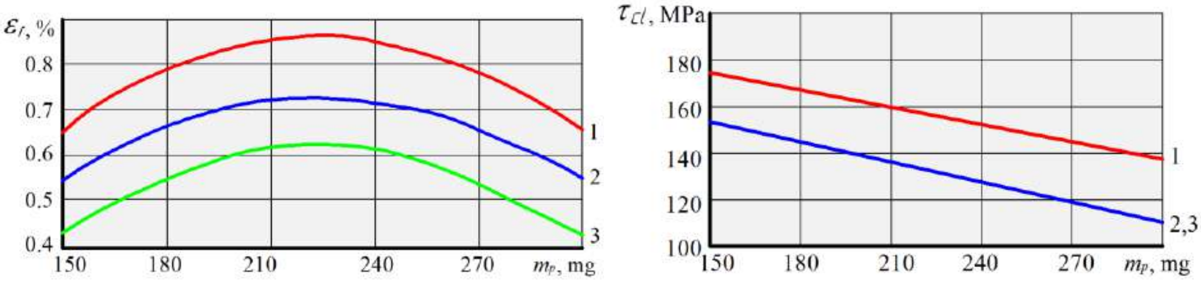


a) b)

Fig. 3. Dependence of elastic modulus of coating E_C (a) and shear bond strength σ_K (b) on spraying distance L: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

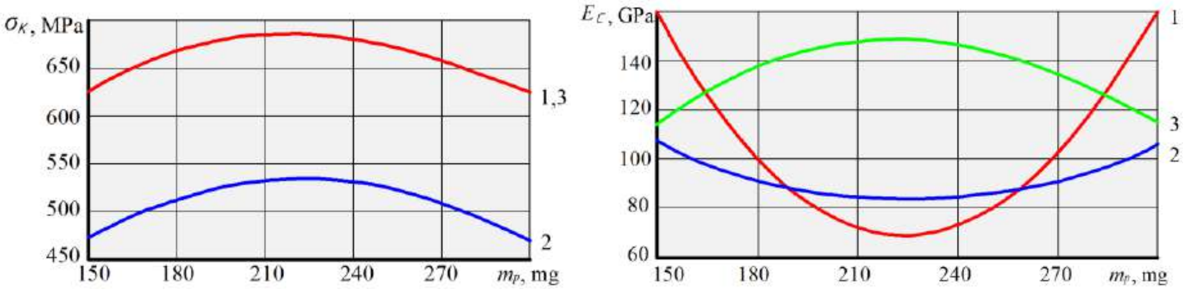
When reducing the spraying distance L to 130 mm, there is a noticeable decrease in the cohesive strength of the coating, and excessive, up to 210 mm, increase of this parameter increases porosity in the interface zone and reduces the adhesive strength of the system "coating – base". There is an overheating of the coating and its cracking under the action of thermal stresses. Note, however, that the increase up to 210 mm leads to a slight increase of E_C (Fig. 3, a) and σ_K (Fig. 3, b) of the coating. This is obviously due to the improvement of cohesive and chemical bonds between the layers during the formation of multilayer coating.

Such a technological parameter of detonation spraying, such as powder weight per cycle m_p, also has a significant effect on the properties of coatings (Fig. 4-5).



a) b)

Fig. 4. Dependence of critical coating fracture deformation ε_r (a) and shear bond strength τ_{cl} (b) on powder weight m_p: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01



a) b)

Fig. 5. Dependence of shear bond strength σ_K (a) and modulus of coating elasticity E_C (b) on powder weight m_p: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

Moreover, ε_r (Fig. 4, a), τ_{cl} (Fig. 4, b), σ_K (Fig. 5, a), E_C (Fig. 5, b) have extreme values at the weight m_p, about 225 mg/cycle. When increasing the powder weight m_p, from 150 to 300 mg/cycle, there is a decrease (by 26-30%) in the adhesion strength of coatings τ_{cl} (Fig. 4, b), because the location and nature of the powder cloud distribution in the barrel of the unit changes, which significantly affects the speed and temperature of the sprayed powder particles.

It was found that the dependence of E_C on the coating thickness h, has an extreme character (Fig. 6). This should be explained by the influence on this characteristic of the uneven distribution of multicomponent coating chemical elements over the thickness, as well as changes in the chemical composition at the interface "coating – base", associated with the occurrence of diffusion interaction of chemical elements included in the coating and the material of the hardened part.

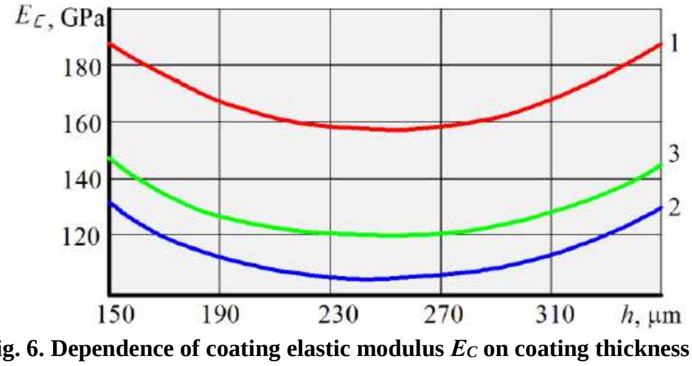


Fig. 6. Dependence of coating elastic modulus E_C on coating thickness h: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

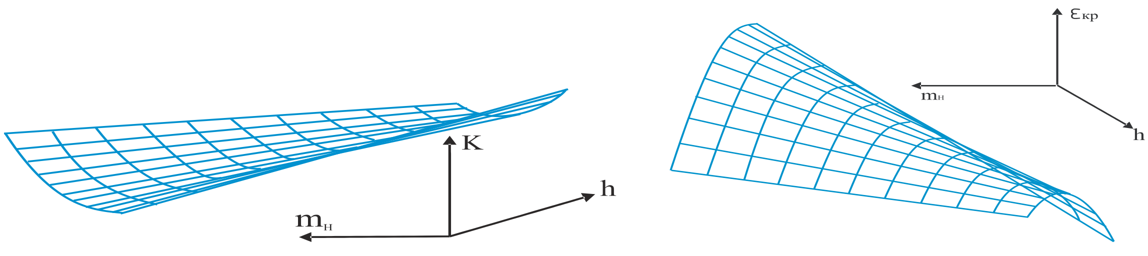
Based on the results presented above, it can be concluded that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the composition of the sprayed coating material, which is due to the difference in their thermophysical, chemical and mechanical properties, as well as physical and chemical processes occurring during the formation of the sprayed layer.

The experimental results were analyzed and mathematical models were verified according to the methodology described in work [16]. The models were calculated using a package of application programs.

Dependences of coating fracture critical deformation, modulus of coatings elasticity, adhesive shear strength, cohesive strength, specific technological cost of coating application, criterion of adhesion-cohesion equal strength on technological and constructive factors were obtained by regression statistical analysis and presented in work [4]. The experimental-statistical approach, which was applied to the study of the coating application process by detonation spraying, allowed to obtain dependences of coating properties on technological and design factors.

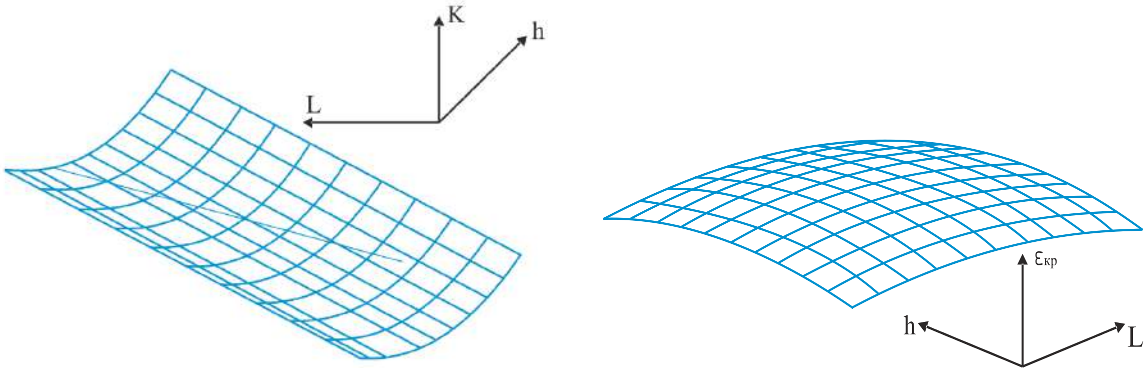
The complex analysis of the obtained data makes it possible to evaluate the influence of the studied factors on the properties of coatings.

The technological process of detonation spraying is characterized by a significant number of technological and design parameters that affect the obtaining of the required properties of coatings. Establishment the optimal technological parameters of detonation spraying is the most important task, the solution of which will make it possible to obtain coatings with the required properties. Fig. 7-8 show the response surfaces of the selected criteria of detonation spraying technology, from which we can see a rather complex influence of the input parameters (factors) of this coating technology on the dependent variables.



a) b)

Fig. 7. Response surface of the regression dependence *K=f(Xi)*. (a) and ε_{KP}*=f(Xi)* (b)



a) b)

Fig. 8. Response surface of the regression dependence *K=f(Xi)*. (a) and ε_{KP}*=f(Xi)* (b)

When selecting optimal spraying modes for detonation spraying, it was found that the quality of coatings obtained by this spraying method is characterized not by one, but by several significant coating properties. Therefore, multicriteria optimization of this technology is necessary by determining some compromise point equally satisfying all requirements (Pareto compromise).

Table 2 shows the results of the multi-criteria optimization.

Table 2

Results of multi-criteria optimization of detonation spraying technology

Values of independent variables					Values of dependent variables	
Base material, *M*	Coating material, *C*	Spraying distance, *L*, mm	Powder weight per cycle, m_p, mg	Coating thickness, *h*, µm	ε_r, %	*K*
VT-20	PG10N01	189,4	287,1	164	0,793	0,42
EP-648	PG10N01	208,75	292,9	265	0,43	0,23
EP-718	PG10N01	201,25	278,9	172	0,73	0,543
VT-20	VK-25M	155,6	158,2	242	0,774	0,437
VT-20	PG10N01	151,25	297,7	341	0,639	0,525
VT-20	PS12NVK-01	208,75	293,0	266	0,442	0,106

Comparison of coatings properties obtained in this work with the properties of analogues showed that optimization of detonation spraying technology provided an opportunity to increase the adhesion strength of heat-resistant coatings made of powder alloy VK-25M by 25%, cohesive strength – by 23%, as well as to propose the use of powders PG10N01, PS12NVK-01 for detonation spraying, which are 2...3 times cheaper than those used industrially, while providing a sufficient level of products strength.

Thus, the conducted studies of the technological process of heat-resistant coatings detonation spraying have allowed to obtain multifactor mathematical models that allows to select technological and design factors that ensure the obtaining of detonation coatings with given mechanical properties.

Conclusions

The presented studies of multi-criteria optimization of heat-resistant coatings detonation spraying technology allowed us to draw the following conclusions:

1. The expediency of detonation coatings optimization taking into account the critical deformation criteria of coating fracture, technological cost of the coating process and adhesion-cohesion equal strength of the coating has been substantiated.

2. Taking into account the methods of expert evaluation, as well as in order to clarify the specific technological cost of coating application, technological and design parameters for optimization of detonation spraying technology were selected.

3. The obtained values of strength properties of the studied detonation coatings at change of technological and constructive factors have shown that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the composition of the sprayed coating material.

4. Multicriteria optimization of heat-resistant coatings detonation application technology provided the possibility of increasing the adhesion and cohesive strength of coatings, as well as significantly reduce the cost of the coating process.

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Солових Е.К., Шепеленко І.В., Черновол М.І., Шумляківський В.П., Солових А.Е., Катеринич С.Е. Багатокритеріальна оптимізація технології детонаційного напилення жаростійких покриттів

Представлені результати досліджень багатокритеріальної оптимізації технології детонаційного напилення жаростійких покриттів. Як критерії оптимізації технології детонаційного напилення обрано: критичну деформацію руйнування покриття, адгезійно-когезійну рівноміцність покриття та питому технологічну собівартість нанесення покриття. Отримано залежності значень міцнісних властивостей досліджуваних детонаційних покриттів при зміні технологічних і конструктивних факторів. Встановлено, що найбільший вплив на механічні властивості досліджуваних детонаційних покриттів мають матеріал деталі, що зміцнюється, і склад матеріалу напилюваного покриття. Це зумовлено відмінністю їх теплофізичних, хімічних і механічних властивостей, а також фізико-хімічними процесами, які відбуваються під час формування напилюваного шару. На підставі дослідження технологічного процесу нанесення детонаційних покриттів отримано багатофакторні математичні моделі, які дають змогу визначити поєднання технологічних і конструкційних факторів, за яких можливе отримання детонаційних покриттів із заданими механічними властивостями.

Ключові слова: детонаційне напилення, жаростійкі покриття, багатокритеріальна оптимізація, конструкційні та технологічні фактори, механічні властивості покриттів.

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Vibration diagnostics of machine friction units: analysis of the current state and prospects

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Abstract

Vibration diagnostics makes it possible to detect defects in the friction parts of the machine at the early stages of their development, which provides for the repair or replacement of parts before they fail. In this work, an analysis of modern research on the use of vibration diagnostics in tribology is carried out, which includes aspects: vibration diagnostics in technology and tribology; vibration during friction and wear; vibration assessment methods; theoretical approaches in the analysis and modeling of vibrations. It is noted that an important aspect is the development and implementation of theoretical approaches in the analysis and modeling of vibrations, which allows a deeper understanding of the dynamics of friction and wear. This approach makes it possible to develop accurate and adaptive strategies for maintenance and optimization of tribotechnical parameters. It is shown that vibration diagnostics is not only a tool for detecting malfunctions, but also a key element for ensuring the long-term and efficient functioning of friction units of machines. The effective use of vibration diagnostics can significantly reduce maintenance costs, increase the reliability and productivity of equipment, which becomes an indispensable condition for the effective functioning of modern technical systems.

Key words: wear, friction details, vibrations, diagnosis, repair, forecasting

Introduction

Machine friction units make up no more than 5-7% of the mass of machines as a whole, it is minor changes in mass or physical and mechanical properties and geometric parameters of triboelements that cause up to 80% of all failures in the operation of machines and mechanisms. Agoone of the main directions of research is the study of friction, lubrication and wear of the surfaces of parts, as well as diagnosing their condition by various methods that are in a complex interaction. Currently, various methods are used to monitor the state of friction nodes, including vibration analysis, acoustic diagnostics, analysis of lubricants and wear products, and others. The application of vibration analysis is one of the most effective methods due to the simplicity of its implementation in online monitoring. However, it remains challenging to extract and process useful wear-related vibration signals and develop specific vibration-based indicators for wear characterization and monitoring. Combinationachievements of tribology and vibration mechanics opens up prospects for solving a number of topical problems related to increasing the wear resistance of contacting surfaces and reducing the level of vibrations in mechanical dynamic systems. In the context of optimizing the tribotechnical parameters of friction nodes, vibration diagnostics becomes an important tool for detecting and monitoring the condition of the equipment. An important direction in this topic is conducting experimental studies aimed at determining the relationship between contact interaction and tribological behavior of materials, taking into account the structure of vibrations. The basis for such research is a thorough substantiation of methods of processing vibration oscillations. This approach allows you to respond to different types of defects, such as cracks, wear, other damage or abnormal operating conditions.

Vibration diagnostics allows detecting defects in the early stages of their development, which allows repair or replacement of parts before they lead to serious breakdowns. Vibration monitoring helps determine optimal operating modes for specific friction assemblies, which can improve their service life and overall performance. Thanks to the early detection of problems, it is possible to avoid expensive repairs and save resources. Regular monitoring of the state of friction nodes allows you to plan maintenance, avoid unexpected failures and reduce costs for scheduled maintenance.

In this work, an analysis of modern research on the use of vibration diagnostics in tribology is carried out, which includes: vibration diagnostics in technology and tribology; vibration during friction and wear; vibration assessment methods; theoretical approaches in the analysis and modeling of vibrations.

Vibration diagnostics in technology and tribology

Vibration diagnostics shows its importance in engineering and tribology - fields that investigate the interaction of friction, wear and lubricants. In the context of these industries, vibration diagnostics becomes not only a method of identifying problems, but also a tool for studying and optimizing tribotechnical parameters, ensuring stable and productive operation of equipment.

The following are the main stages of tool diagnostics in technology and tribology:

- inuse of vibration sensors to collect information about vibrations at various points of the equipment;
- Processing and analysis of collected data to determine frequencies, amplitudes and other parameters of vibrations;
- comparison of analysis results with standards to detect any abnormal deviations;
- determining the forecast of the technical condition and developing strategies for optimizing the parameters of friction nodes.

Machines generate vibration during operation, and unwanted vibrations occur that disturb the machine's system, resulting in malfunctions such as imbalance, wear, and misalignment. Thus, vibration analysis has become an effective method of monitoring machine health and performance. Machine vibration signals contain important information about the machine's condition, such as the source of the fault and its severity. Operators also receive early warning for scheduled maintenance. Over the years, numerous approaches to machine vibration data analysis have been proposed, and each approach has its own characteristics, advantages, and disadvantages. The article "Vibration analysis, practical control of machines for technological installations" [1] presents a systematic review of modern vibration analysis for machine monitoring and diagnostics. It involves data collection (applied tool such as analyzer and sensors), feature extraction and fault recognition methods using artificial intelligence. Answers to several research questions have been provided. A combination of time-domain statistical functions and deep learning approaches is expected to be widely used in the future, where fault characteristics can be automatically extracted from raw vibration signals. The availability of a variety of sensors and communication devices in new intelligent machines will be a new and huge aid to vibration monitoring and diagnosis.

Vibration and wear product analysis are the two main condition monitoring techniques for machine maintenance and fault diagnosis. In practice, these two techniques are usually performed independently and can diagnose only about 30-40% of faults when used separately. However, recent evidence shows that combining these two methods provides greater and more reliable information, resulting in a more efficient maintenance program with significant economic benefits to industry. Correlation of vibration analysis and wear residue analysis was investigated [2]. An experimental test bench consisting of a worm gear and driven by an electric motor was created to test the correlation of the two methods under different wear conditions. Three tests were performed under the following conditions: (a) no proper lubrication, (b) normal operation, and (c) presence of contaminants added to the lubricant. Oil samples and vibration data were collected regularly. Analysis of wear products included investigation of the number and size distribution of particles, investigation of morphology and particle types to determine possible wear mechanisms, and chemical composition analysis to assess the sources of wear. Fault detection in the vibration signature was compared to particle analysis. The results of this paper provided a better understanding of the dependent and independent role of vibration and wear product analysis in machine condition monitoring and fault diagnosis.

Smooth and trouble-free operation of electric motors is a requirement of modern industry. To ensure this, vibrodiagnostic is perfect. The study [3] analyzes the time and signal spectrum of the two most effective types of signals, i.e., vibration and current, for various electric motor faults. Analysis of the vibration and current signal (temporal and spectral) is performed using signals measured from various faulty electric motors from a laboratory setup. The advantages and disadvantages associated with these traditional procedures are shown. Next, existing research and development in the field of signal automation of condition monitoring methodologies for fault detection and diagnosis of various electrical and mechanical faults of electric motors is presented and summarized. Currently, artificial intelligence methods are used to diagnose malfunctions of electric motors and other machines. Advances in AI-based fault diagnosis, including popular approaches, are reviewed in detail. These methods are integrated with traditional monitoring methods. Overall, this article provides an overview of system signals, conventional and advanced signal processing techniques; however, it mainly covers the selection of effective statistical features, artificial intelligence techniques, and appropriate training and testing strategies for electric motor fault diagnosis.

Vibration damage detection has virtually no alternative for rotating steam turbine shafts during operation. To date, many vibration detection methods have been developed. But the effectiveness of all these methods depends very much on the type of structure, the way it is deformed and the type of damage. At the moment, practical engineers do not have a tool for correctly choosing the most suitable method of detecting damage to a particular structure. Comparative evaluation of the effectiveness of different methods of vibration diagnostics for detecting damage up to a critical size is a complex and time-consuming process. Thus, a rather simple method of choosing the most effective vibration method of damage detection for a certain structure with a certain type of cracks and with a certain type of deformation was developed [4]. This method is based on determining the relative change in shaft compliance due to a crack using linear fracture mechanics. As an example, a comparative analysis of the sensitivity of several vibration detection methods to the presence of a longitudinal and transverse crack in the shaft during bending and torsional vibrations was carried out.

Wind power, which is one of the fastest growing sources of renewable energy, also has a high failure rate and O&M costs. Thus, condition monitoring and fault diagnosis of a wind turbine generator set are essential. Among the various components of a wind turbine generator set, the planetary gearbox plays a crucial role in the transmission and leads to a relatively higher failure rate and longer downtime. In this regard, a number of studies were published in academic journals and conference materials. The article "Vibration-Based Condition Monitoring and Fault Diagnosis of Wind Turbine Planetary Gearbox" [5] provides a systematic and relevant modern review of wind turbine planetary gearbox condition monitoring methods on the topics of fundamental analysis, signal processing, feature extraction, and fault detection. In addition, several valuable open questions are pointed out and potential research directions are suggested.

Having analyzed the articles [1-5], we have an intermediate conclusion that vibration diagnostics is an effective tool for improving the technical condition of friction units of machines. Timely detection of defects, optimization of work modes and cost savings make this method an integral part of tribotechnical management strategies. The use of vibration diagnostics allows you to maintain the equipment in an effective and reliable working condition, contributing to the extension of its service life and the reduction of maintenance costs.

Vibrations during friction and wear

In the process of friction and wear, vibrations occur, which can indicate various aspects of the technical condition of the equipment. Vibrations can occur due to uneven surfaces, improper lubrication, material defects, or malfunctions of friction units. Vibration diagnostics allows you to detect these vibrations and identify their sources.

Vibration analysis is a powerful diagnostic tool, and troubleshooting major technological mechanisms would be unthinkable without modern vibration analysis. There are many ways in which vibration data can be acquired and displayed to detect and identify specific problems in rotating machinery. By far the most important of these methods involve measuring vibration amplitude and frequency data. There are dozens of different data collectors and/or data collection modules available for this task.

The frictional force between sliding surfaces arises as a result of various and complex mechanisms and can cause undesirable dynamic characteristics of many mechanical systems. The laws of friction are phenomenological in nature because they are based on quantities that can be observed and measured. The mechanics of contact and friction of metal-metal and elastomer-metal contact surfaces are considered [6]. Unfortunately, there is no satisfactory method for determining or measuring the area of contact between sliding bodies. Both dry friction and lubricated friction are considered. Modeling the friction force in mechanical systems depends on several factors. These include material properties and geometry of sliding surfaces, surface roughness, surface chemistry, sliding speed, temperature, and normal load. Other factors include the effects of normal and tangential vibrations on static friction. Here, static friction is considered as a special case of kinetic friction. This basis is important for the study of friction-induced vibration.

Vibrations can directly affect the coefficient of friction. The change in the friction coefficient with a change in the vibration frequency and relative humidity on a mild steel disc was experimentally investigated[7]. The Pin-on-disc type apparatus is used for the experiment, which has the ability to vibrate the disc with different frequencies and amplitudes. During the experiment, the normal load, speed and relative humidity were varied. It was found that the coefficient of friction under conditions of no vibration is higher than under conditions of vibration, and the values of the coefficient of friction decrease with an increase in the frequency of vibration. Likewise, the friction coefficient decreases with increasing relative humidity. It was also observed that the rate of reduction of the friction coefficient has a certain relationship with the frequency of vibration and relative humidity.

The theory from the previous paragraph is confirmed by other studies [8]. The object of the study was the effect of external vibrations on the force of friction using different frequencies, amplitudes, loads and materials. The results show that it is possible to influence the force of friction between two contact surfaces using vibration. The force of friction can be weakened mainly due to separation of surfaces or increased by welding phenomena on contact surfaces. Experiments have shown that by changing one of the parameters, surface pressure, frequency or amplitude, it is possible to obtain either an increase or a decrease in frictional forces. Surface roughness, direction of vibration, relative velocity and materials can also play a determining role. Thanks to vibration support, the tendency to slip is reduced or eliminated.

Another study in this area provided new insight into the nature of the system's motion and the load–velocity–friction relationship. Thus, in the article [9], a tribological study of the macroscopic manifestation and characteristics of sliding friction was carried out. The aim of the task was to measure the friction in lubricated sliding contacts and to check the interaction between the environment (test stand) and the experimental friction contact. Vibrations caused by friction were observed and studied as a manifestation of the process. The standard set of speed and force/torque sensors has been supplemented with a multi-channel vibration detection system. The operating modes of the system were identified using spectral analysis in confrontation with the natural vibration frequencies of the subsystems of the test stand.

Vibration assessment methods

There are several methods for evaluating vibrations in machine equipment. Among the most common are vibrometers (accelerometers), as well as the use of spectrum analyzers and filters for the selection of specific vibration components. Let's consider some real studies in this area.

Vibration-based structural performance monitoring methods are one of the most common approaches to structural damage identification. The presence of damage in structures can be determined by monitoring changes in dynamic behavior under external loading, and is usually performed using experimental modal analysis or operational modal analysis. These tools typically require a limited number of physically connected transducers (such as accelerometers) to record the structure's sensor parameters for further analysis. Sensors, wires, wireless receivers, and a data acquisition system are also typical components of traditional sensor systems. However, equipping lightweight structures with contact sensors such as accelerometers can introduce mass-loading effects, and for large-scale structures, instrumentation is laborious and time-consuming. Achieving high spatial resolution measurements for a large-scale structure is not always possible when working with traditional contact sensors, and there is also the potential for insufficient reliability associated with fixed contact sensors that will outlive the life of the main structure. Among the state-of-the-art non-contact measurements, digital video cameras are capable of rapidly collecting high-density spatial information from structures at a distance. In this paper, subtle motions from recorded video (i.e., image sequences) are extracted using Phase-based Motion Estimation (PME), and the resulting information is used to identify wind turbine damage. The PME and incremental motion-based approach estimates structural motion from a captured image sequence for both baseline and test cases of wind turbine blade damage. The operational deflection shapes of the test articles are also quantified and compared for the base and damaged states. Additionally, having adequate lighting can be a challenge when working with high-speed cameras, so image enhancement and contrast adjustments were also performed to improve the raw images. Ultimately, the selected resonant frequencies and deflection waveforms are used to detect the presence of damage, demonstrating the feasibility of implementing non-contact video measurements to perform realistic structural damage detection[10].

In the work "Method of visual characteristics of vibration for intelligent diagnosis of malfunctions of rotating machines" [11] a new method of diagnosis of malfunctions based on visual selection and characteristics of vibration is proposed. Instead of using conventional accelerometers to obtain fault data, the visual diagnosis method obtains full vibration information with rich vibration characteristics and does not create a mass load effect on the measured object. This method obtains time-domain vibration information from collected image sequences through image phase difference and then encodes it into grayscale images as input to a convolutional neural network model. Experimental test results on a bearing vibration image dataset show that the proposed method can achieve excellent performance in fault diagnosis. It provides excellent results with high classification and recognition accuracy.

The paper [12] provides an overview of the methods of vibration and acoustic measurements for detecting rolling bearing defects. Detection of both localized and distributed categories of defects is considered. The occurrence of vibration and noise in bearings is explained. Vibration measurements in both the time and frequency domains were considered, as well as signal processing techniques such as high-frequency resonance techniques. Other acoustic measurement methods such as sound pressure, sound intensity and acoustic emission were considered. Recent trends in bearing defect detection research, such as the wavelet transform method and automated data processing, have also been included.

The vibration diagnostics method is also used to monitor the state of ball bearings. Since the vibration graph reveals important information about the development of a defect in them [13]. Analysis of the time-domain vibration signature, such as peak-to-peak amplitude, rms, cross factor, and kurtosis, indicates ball bearing defects. However, these factors do not determine the position or nature of defects. Each defect causes a characteristic vibration in ball bearings. Therefore, the study of the vibration spectrum can provide information about the type of defects. In this article, a test bench was developed and a pair of brand new commercial ball bearings were installed. Bearings operate throughout their service life under constant speed and load conditions. During the test, vibration signatures are recorded and statistical indicators are calculated. When anomalies are detected in the statistical measurements, vibration spectra are acquired and examined to determine where the defect is located on the running surfaces. At the end of the test, the ball bearings are disassembled to take microscopic photographs of the defects.

For the quantitative diagnosis of rolling bearing malfunctions, a nonlinear vibration model was created in the study [14] to assess the severity of rolling bearing malfunctions. The defect size parameter of the outer ring is entered into the dynamic model, and the vibration response signals of the rolling bearings at different defect sizes are simulated. The signals are analyzed quantitatively to observe the relationship between vibration response and defect sizes. The points of impact, when the ball rolls on and away from the defect, are determined by the vibration response signals. Next, the impact characteristic is obtained based on the time interval between the two impact points, which reflects the severity of the malfunction in the rolling bearings. When the bearing fracture width is small, the signals are presented as a distinct single shock. The signals gradually become double shocks as the size of the defects increases. The vibration signals of the rolling bearing test rig are measured for different sizes of damage to the outer ring. The experimental results are in good agreement with the simulation results. These results are useful for understanding the vibration response mechanism of rolling bearings under different fault severities.

From the articles [11-14], we can see that there are a large number of different methods of vibration assessment, from traditional vibrometer measurements to acoustic and photo observations. Each method has its advantages and disadvantages, but all of them are aimed at identifying and qualitatively assessing the condition of machines and mechanisms.

Theoretical approaches in the analysis and modeling of vibrations

The study and analysis of vibrations in machine equipment plays an important role in ensuring the reliability and productivity of technical systems. Theoretical approaches in the analysis and modeling of vibrations make it possible to understand the dynamics of the interaction of friction, wear and structural elements of equipment. In this article, we will consider the key aspects of theoretical approaches, their influence on the development of vibration diagnostics and the importance of improving tribotechnical parameters.

One of the main components of theoretical approaches is the development of mathematical models for describing vibrations in friction and wear systems. Models can include various factors such as stiffness, damping, mass, and other parameters that determine the dynamics of the system. The development of mathematical models makes it possible to accurately analyze various interactions and predict the behavior of systems in various conditions.

Analysis of deformations and stretching of materials allows to determine the influence of vibrations on structural components of machines and friction nodes. Dynamic systems study the interaction of objects taking into account temporal and spatial parameters, helping to build complex models of dynamics.

Consideration of tribological aspects is important for understanding the effect of friction and wear on vibrational dynamics. Modeling of tribosystems allows to analyze the effect of lubrication, properties of lubricants and other tribological parameters on equipment vibrations.

Theoretical approaches should always be accompanied by experimental confirmation. Real vibration data allow you to check the adequacy of mathematical models and improve them for more accurate forecasts and analysis of the influence of external factors. Let's consider several experimental studies on various equipment with the analysis of vibration oscillations.

In the work "Signal processing methods for estimating rolling bearing defects" [15], signal processing methods are proposed for selecting entry and exit points from the bearing vibration signal to estimate the size of the defect. The entry point is the starting point of the low-frequency response when the rolling element enters a localized defect in the raceway that is contaminated with background noise and difficult to identify. For effective identification of the entry point, a signal processing method based on an empirical model is proposed. A variational decomposition mode is applied to the bearing input signal for more accurate estimation. The differentiation technique is used to identify the high-frequency exit point with more reliable threshold values for automatic diagnosis. Then, based on the defect size estimation models for both the inner and outer ring defects, the defect size can be estimated. The proposed methodology is tested on the machine tool spindle bearing system. Experimental results show that the proposed signal processing methods provide less biased spindle speed results and more accurate estimation.

Time-frequency analysis can give a general idea of the behavior of friction-induced vibration. In the article [16], the short-time Fourier transform, the Wingner–Will distribution, the Choi–Williams distribution, and the Zhao–Atlas–Marx distribution are used to analyze the time-frequency characteristics of friction-induced vibration. The result shows that there is always a frequency change in the frequency-time representation of the vibration at the location where the vibration is confined. Frequency changes in time-frequency representations are related to the nonlinearity of vibration systems. The nonlinearity can be considered as evidence to support the idea that friction-induced vibrations are limited to limit cycles due to the nonlinearity of the system. On the basis of the frequency-time representation of oscillations, it can be concluded that the frictional vibration system is generally a linear system in the phase of vibration occurrence, but is a nonlinear system in the phases of limitation and disappearance of vibration.

Another model is proposed in the article "Damage diagnostics using time series analysis of vibration signals" [17]. It presents a novel time series analysis to identify the sources of damage in a mechanical system operating in various operating environments. The source of the damage is determined solely by analyzing the acceleration time history recorded from the structure of interest. First, a data normalization procedure is proposed. This procedure selects a reference signal that is "closest" to the newly obtained signal from an ensemble of signals recorded when the structure is undamaged. Second, a two-stage prediction model is built based on the selected reference signal (a combination of autoregression and autoregression methods with exogenous inputs. Then the residual error, which is the difference between the actual acceleration measurement for the new signal and the prediction obtained from the model developed on the basis of the reference signal, is defined as a damage-sensitive function. This approach is based on the premise that if a structure has been damaged, a prediction model previously defined using an undamaged time history will not be able to reproduce the newly obtained time series measured from the damaged structure. Furthermore, increasing residual errors will be maximized on sensors installed close to the actual damage locations.The applicability of this approach is demonstrated using acceleration time histories obtained from an eight-degree-of-freedom mass-spring system.

The autoregressive model was studied in detail in the article "Non-stationary modeling of vibration signals for monitoring the condition of machines" [18] and the corresponding processes of feature selection and condition monitoring. For the analysis, an orthogonal transformation is introduced both to compress the features and to create a statistical model of the template representing the normal state. Finally, the measure of monitoring is determined using pattern recognition theory similarity analysis. An example of vibration monitoring of a reciprocating hydraulic pump shows how the proposed method can be used.

Another type is "Cyclostationary simulation of vibration signals". The study of [19] is to demonstrate that machine signals require special processing that is much more subtle than that of communication signals, from which the cyclostationarity paradigm originally arose and was developed for. First, different types of cyclostationarity are distinguished, covering many signals of a rotating machine. In particular, the importance of considering pure and not impure cyclostationarity is emphasized. Next, the relations between cyclostationarity of angle and time are investigated and some useful results are obtained. It is shown that the vibration signals exhibit cyclostationarity if and only if the random fluctuation of the machine speed is periodic, stationary or cyclostationary. As a result, a comprehensive methodology for the processing of actual cyclostationary signals is proposed: three typical examples are presented concerning the vibration signals of an internal coupling motor, a gearbox and a rolling bearing, each of which is characterized by a different type of cyclostationarity.

This theory is confirmed in the article "Cyclostationary processes: application in early diagnosis of malfunctions" [20]. It presents the theory of cyclostationary processes as a powerful tool for diagnosing rotating machines. It is shown that the well-known method of synchronized averaging is an expression of the first-order cyclostationarity, and the spectral correlation function obtained from the second-order cyclostationarity is an effective parameter for the early diagnosis of rotating machine faults. In addition, it is shown that the vibration signals measured on gear systems exhibit second-order cyclostationarity. The application for early diagnosis of chipping in gear teeth demonstrates the power of this new parameter.

Conclusions

1. At the current stage of development of the field of surface engineering, when technologies are developing rapidly and requirements for equipment reliability and productivity are constantly increasing, vibration diagnostics becomes a crucial element of strategies for managing the technical condition of machines and optimizing their tribotechnical parameters.

2. Directions for the use of vibration diagnostics for assessing the condition of friction units of machines are presented. It has been established that vibration diagnostics is an integral component of modern technical maintenance and management of machinery. The vibrodiagnostic technique allows for timely detection and analysis of various defects and anomalies in the operation of friction units, providing the possibility of preventing serious breakdowns and general improvement of machine reliability. Early detection of defects, optimization of operating modes and effective management of tribotechnical parameters make vibration diagnostics a necessary component to ensure the stability and efficiency of technical systems.

3. An important aspect is the development and implementation of theoretical approaches in the analysis and modeling of vibrations, which allows a deeper understanding of the dynamics of friction and wear. This approach makes it possible to develop accurate and adaptive strategies for maintenance and optimization of tribotechnical parameters.

4. It is shown that vibration diagnostics is not only a tool for detecting malfunctions, but also a key element for ensuring the long-term and effective functioning of friction units of machines. The use of this approach can significantly reduce maintenance costs, increase the reliability and productivity of equipment, which becomes an indispensable condition for the effective functioning of modern technical systems.

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Литвинов О.О., Диха О.В. Вібродіагностика вузлів тертя машин: аналіз сучасного стану та перспективи

Вібрайійна діагностика дозволяє виявляти дефекти деталей тертя машини на ранніх стадіях їх розвитку, що передбачає проводення ремонту або заміну деталей до того, як вони відмовлять. В даній роботі проведений аналіз сучасних досліджень застосування вібродіагностики в трибології, що включає аспекти: вібродіагностика в техніці і трибологіі; вібраціі при терті і зношуванні; методи оцінки вібрацій; теоретичні підходи при аналізі і моделюванні вібрацій. Зазначено, що важливим аспектом є розробка і впровадження теоретичних підходів при аналізі і моделюванні вібрацій, що дозволяє глибше розуміти динаміку тертя та зношування. Такий підхід дозволяє розробляти точні та адаптивні стратегії обслуговування та оптимізації триботехнічних параметрів. Показано, що вібродіагностика є не лише інструментом для виявлення несправностей, але і ключовим елементом для забезпечення тривалого та ефективного функціонування вузлів тертя машин. Ефективне застосування вібраційної діагностики може суттєво зменшити витрати на технічне обслуговування, підвищити надійність та продуктивність обладнання, що стає невід'ємною умовою для ефективного функціонування сучасних технічних систем.

Ключьові слова: зношування, деталі тертя, вібрації, діагностування, ремонт, прогнозування

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Uninterrupted control of coating thickness during the wear process of vehicle units

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Abstract

In the course of this research in the field of automotive technology, systematic patterns and features of wear of structural materials with wear-resistant coatings that were applied using various technologies, depending on the change in friction modes, were revealed. Our research led to the identification of physical parameters of tribological properties and their changes in the friction process.

An interesting property discovered in the course of our work is the fact that changing the contact area several times does not significantly affect the change in the friction coefficient. Instead, changes in the coefficient of friction are mainly related to the chemical composition of the secondary structures that are formed during friction.

An important aspect of our findings is that the change in the coefficient of friction is usually due to the chemical composition of the secondary structures, which in turn depend on the chemical composition of the base material, the characteristics of the coating, the characteristics of the environment and the temperature conditions in the friction zone. An analysis of the chemical composition of secondary structures formed during friction was carried out, which allows for a deeper understanding of wear mechanisms and creates opportunities for optimizing materials and coatings in the field of automotive technology.

Keywords: wear, coatings, automatic measurement, thickness, chemical composition.

Introduction

Over the past decades, wear-resistant coatings have been widely used in various fields of human activity, performing various functions under different conditions - from chemical composition to application methods. This direction is extremely important, because the development of multilayer or combined coatings is equivalent to the creation of a new material with unique properties.

During the development of new coatings, laboratory studies of wear resistance are an important stage, which make it possible to predict the duration of operation of the tribocouple with the coating. The formation of secondary structures under the influence of specific conditions and modes of friction solves one of the key tasks - determining the thickness of the coating.

Insufficient or too large coating thickness can significantly affect the result: the difference in adhesion indicators and insufficient tribological effect from the first case, or the risk of rupture due to internal stresses from the second case. That is, the thickness of the coating plays a decisive role in achieving the desired indicators of wear resistance.

One of the important aspects is establishing the nature and dynamics of the process of wear of the coating over time. Knowing the necessary and sufficient thickness of the coating allows you to effectively influence the results of operation, and the detection of optimal values guarantees maximum indicators of wear resistance. Methods of determining the wear resistance of coatings, aimed at establishing tribological characteristics, play a key role in this process.

To determine the tribological characteristics of coatings in the field of automotive technology, it is necessary to focus on measuring and controlling the thickness of these coatings during their operation. The coating thickness usually ranges from a few micrometers to hundreds of millimeters, which is important to consider when analyzing its tribological properties in the automotive industry.

According to the recommendations of the GOST 30431-96 (DSTU 3366-96) standard for automotive tribological studies (autotribology), it is important to pay attention to point 4.4, where it is stated that the lapping of the coated sample should take place at a speed of 0.7 m/s and a pressure of 1 MPa to values of the roughness parameter from 0.2 to 0.3 μm. If the transition from the technological microrelief to the operational one takes less than 15-35 minutes, using the specified parameters, then a gradual increase in pressure up to 3 MPa, testing of various options for increasing the sliding speed should be considered. The maximum possible sliding speed is 3 m/s in the context of automotive research.

Before running in the sample with the coating, it is necessary to carry out a similar process with the base sample without coating. In thin-layer coatings, in particular thin films, their partial or complete wear is observed. It is important to consider that there are coatings that are used in the automotive industry to improve the wear resistance of assemblies, and whose tribological characteristics can be difficult to determine using standard techniques, especially if they are relatively soft and have a small thickness.

As a result of exposure to uncontrolled high specific pressures and temperatures during processing, a change in the internal structure may occur on the surface of the sample or a certain part of it. Accordingly, research results may be limited and used only for comparative analyses. In the automotive field, all these factors introduce significant errors into the final conclusions and results regarding materials and coatings. Using standard methods allows you to establish the tribological properties of both the coating itself and the base material, but this leads to obtaining average values, since it can be difficult to distinguish between the wear of the base and the coating.

Usually, determination of the thickness of car coatings is carried out by a chemical method. The sample, usually a plate, is covered with a layer of material, and then the base is chemically dissolved, leaving only the coating (foil), which is weighed. This approach is relatively accurate and simple. However, to establish wear resistance, friction coefficient and other tribological parameters, it is necessary to use experimental methods using mechanical action.

In addition, it is important to establish the optimal, as thin as possible thickness of the coating, which would prevent intensive wear, considering that thick coating layers do not always guarantee a high-quality and durable coating.

In the automotive industry, there are tribological pairs, such as coating-substrate or coating-coating (in the case of multi-layer coatings), which exhibit high wear resistance despite their small thickness (a few micrometers). Studies show that with an increase in the thickness of the coatings, even a small amount of wear can become more intense [1-3]. This confirms that tribological methods should be used to evaluate the tribological characteristics of coatings, and not any other approaches.

In general, the interaction of friction in the field of automotive engineering is an extremely complex process, which at the moment is almost impossible to completely describe mathematically for any conditions. Thus, the friction properties of materials are studied with the help of experiments. The obtained results can be used to develop mathematical models and engineering calculations.

Increasing the wear resistance of automotive parts can be achieved at the design stage, using technological methods, as well as during operation. Among the most common methods of increasing wear resistance in the automotive industry is the use of technological methods.

One of the ways to protect the friction unit from wear in the automotive sector is to use wear-resistant coatings using various technological methods. Application of composite and multi-layer coatings is carried out in various ways, such as powder sintering, surfacing, galvanic methods and others.

Understanding the characteristics of each material used in complex multilayer or composite coatings, predicting the behavior of such a composite becomes a challenge, as it depends on many factors: chemical composition, proportions of components, application technology and thickness of the coating itself. The interaction of heterogeneous elements leads to an effect equivalent to the creation of a new material [1], the properties of which differ from the properties of each individual component in terms of qualitative and quantitative indicators. The difference in the characteristics of materials is directly related to their composition and structure. In the field of automotive technology, this is especially relevant, since the properties of complex coatings can determine the quality and durability of automotive elements.

According to A. V. Chichinadze [2], the main difficulty in the development of wear-resistant coatings is that in the modern process of designing mechanisms there is no agreed methodology for the optimal use of various methods of strengthening friction nodes.

A. S. Vereshchak [3], considering a cutting tool that works under conditions of high load, tries to use multilayer composite coatings to create tool materials with "ideal properties". However, this task is not an easy one, since the improvement of some parameters usually leads to the deterioration of others. This limits the technological possibilities of using known tooling materials in the automotive industry, as their effectiveness is usually within a limited range of applications.

Purpose and setting of the task

The purpose of this study is to track the process of coating thickness reduction under the influence of wear and analyze the change of tribological parameters during operation, focusing on the context of automotive technology.

Presentation of research materials

Research was carried out on HVG steel (the chemical composition is presented in Table 1) using a modernized tribomachine UMT 2168 [4, 5], specially adapted for the automotive field. This allowed tribological parameters such as linear wear, friction moment and average temperature in the friction zone to be automatically captured and recorded at a frequency of 0.5 seconds, without the need to remove the sample from the rig. The obtained data were processed on a computer for further analysis of the results.

Table 1

Chemical composition of the investigated steels

Steel	Chemical composition, % (weight)									
	C	Si	Su	Mn	No	P	Cr	S	W	Mo
KhVG	0.90-1.05	0.10-0.40	<0.30	0.80-1.10	<0.35	<0.03	0.90-1.20	<0.030	1.20-1.60	<0.30

The steel was heat treated to a Rockwell hardness of HRC 55. After that, the samples were ground to remove the decarburized layer, achieving a roughness Ra of 0.8 to 1.6.

The research was carried out according to the scheme of dry disc-finger friction with a spherical surface (see Fig. 1), which has advantages for automotive subjects: no need for running-in, no distortions and base errors, the possibility of achieving high specific pressures in the contact zone.

The main goal is achieved thanks to the selected spherical working surface of the sample, which does not require additional work-in. Fixation of wear is carried out with the help of a linear displacement sensor, which allows you to determine the wear limit of the coating and the base without interrupting the friction process.

Requirements for the working surface of the specimen include 100% contact with the counterbody and immediate run-in, which is achieved through the use of a spherical friction surface (see Fig. 1).

A series of experiments made it possible to identify several key areas of wear on samples with coatings, which can be conventionally marked in fig. 1: a) the point of contact of the sample with the counterbody at the stage of initial friction, marked as the I-I section and point A (at this moment the maximum specific pressures occur), which ensures immediate work-in and 100% further adhesion of the contacting surfaces; b) the wear area directly of the coating, marked as section II-II and plane B; c) transitional zone of general wear of the matrix and coating, marked as section III-III, wear of the coating (plane C) and base (plane D).

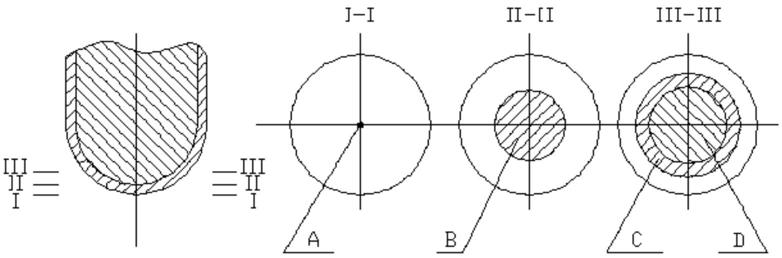

Fig. 1. Stages of wear of the coated sample

To evaluate the resistance to wear, samples made of thermally hardened steel ХВГ (HRC 55) were used. The counterbody is made of high-carbon heat-strengthened steel U10A HRC 62. The tests were carried out according to the "disk - finger" friction scheme with a spherical contact shape (see Fig. 1). The AlN-ZrB2 coating was applied to the sample by electrospark alloying with a thickness of approximately 0.1 mm. The test regime included an initial specific pressure of 1300 MPa and a sliding speed of 0.67 m/s. These experiments are important for the automotive industry, as they allow to determine the effectiveness of materials in friction nodes and provide optimal performance for automotive parts.

As illustrated in Figures 2–4, data obtained during friction are presented. Figure 2 shows the linear wear of the coating and the base, which can be divided into three stages: 1) 0 ... 30 m, 2) 30 ... 400 m, 3) 400 ... ∞. From the information on material consumption during coating, it is known that the thickness of the coating is approximately 0.1 mm.

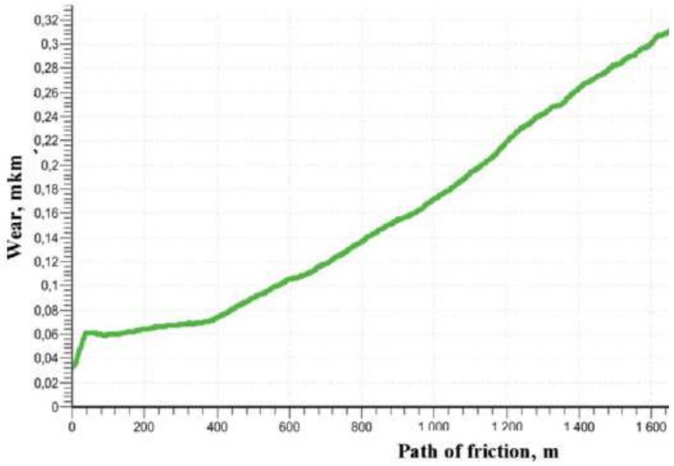

Fig. 2 Change in the value of linear wear from the path of friction

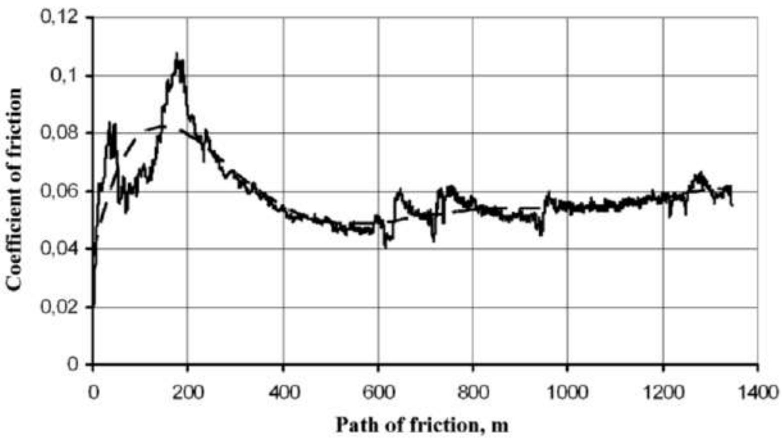

Fig. 3. Variation of the coefficient of friction from the path of friction

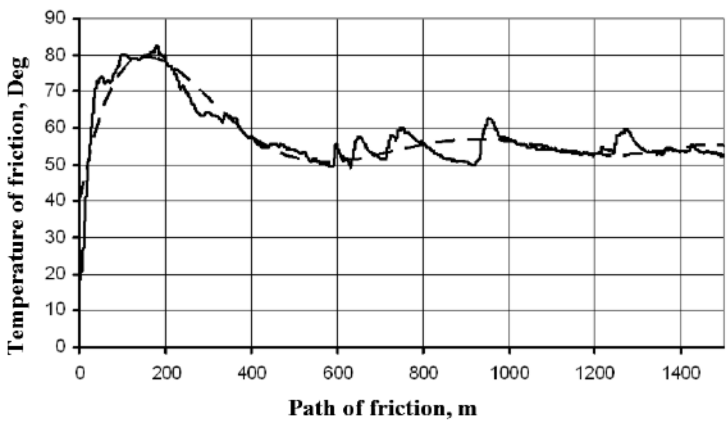

Fig. 4. Change of the average temperature in the friction zone from the friction path

The inflection of the curve when reaching a friction path of 400 m corresponds to wear with a value of h = 0.08 mm (Figure 2), after which the intensity of wear increased. That is, the actual thickness of the coating is 0.08 mm. The tribological properties of this coating and the characteristics of its tribological behavior during friction and wear were also determined.

In addition to the specified tribological characteristics, the technical capabilities of the equipment make it possible to establish the process of changing the friction coefficient, the average temperature in the friction zone, and the intensity of wear. It is well known that the friction coefficient for a certain tribopair under constant friction conditions is constant. Figure 3 shows that the friction coefficient undergoes changes. This change is associated with wear of the coating at a distance of 250 m of the friction path, from 250 to 400 m - wear, partial contact of the microprotrusions of the base (roughness). The number of microprotrusions from 250 to 400 m gradually increased, and therefore the proportion of the surface contact area decreased, which led to changes in the friction coefficient and temperature (Figures 3, 4).

There are cases where accurately defining the boundary between the substrate and the coating becomes a challenge, and therefore a complex of tribological characteristics such as the coefficient of friction, the temperature in the friction region and the intensity of wear must be considered. To obtain more accurate data on the thickness of the coating, especially in the case of diffusion coatings, there is a difficulty due to the smooth transition from a more saturated layer to a less saturated one.

Determining the thickness of such a layer turns out to be a difficult task, since there is a smooth transition from a solid surface to a less solid base. The change in hardness is determined using a hardness tester on a cut and specially prepared sample. This technique is quite time-consuming, it is especially difficult to cut the sample and prepare it, requiring special equipment and high qualification of the laboratory technician.

Figures 3 and 4 show that the relative stability of the tribological parameters occurs after about 500 meters (averaged dashed curve), which is explained by the inertness of temperature indicators and residual friction products. This is important for the automotive industry, as it allows to determine the effectiveness of the materials in the friction nodes and to ensure optimal performance for the automotive parts.

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Маковкін О.М., Вичавка А.А., Вальчук І.К. Безперервний контроль товщини покриття під час процесу зношування вузлів автомобіля

У ході даного дослідження в галузі автомобільної техніки виявлено систематичні закономірності та особливості зношування конструкційних матеріалів із зносостійкими покриттями, нанесеними за різними технологіями в залежності від зміни режимів тертя. Наші дослідження привели до визначення фізичних параметрів трибологічних властивостей та їх зміни в процесі тертя.

Цікавою властивістю, виявленою в ході нашої роботи, є те, що зміна площі контакту кілька разів не впливає істотно на зміну коефіцієнта тертя. Натомість зміни коефіцієнта тертя в основному пов’язані з хімічним складом вторинних структур, які утворюються під час тертя.

Важливим аспектом наших висновків є те, що зміна коефіцієнта тертя зазвичай пов’язана з хімічним складом вторинних структур, які, у свою чергу, залежать від хімічного складу основного матеріалу, характеристик покриття, характеристик навколишнього середовища і температурного режиму в зоні тертя. Проведено аналіз хімічного складу вторинних структур, що утворюються під час тертя, що дозволяє глибше зрозуміти механізми зношування та створює можливості для оптимізації матеріалів і покриттів у сфері автомобільної техніки.

Ключові слова: зношування, покриття, автоматичний вимір, товщина, хімічний склад.

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Performance analysis of turbocharger rotor friction pairs of an automobile engine

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Abstract

Turbochargers are used in modern engines to increase their performance by increasing the amount of air supplied. To increase wear resistance, researchers and engineers are improving integrated technologies for strengthening turbocharger assemblies. The purpose of this study is to evaluate and analyze the influence of integrated strengthening technologies on the wear resistance of the turbocharger assembly. Integrated strengthening technologies include the use of new materials, coatings, design changes and manufacturing processes that improve the strength, thermal stability and wear resistance of the turbocharger assembly. A comprehensive analysis was carried out, including experimental tests, mathematical modeling and numerical simulations. Analyzed tests of wear resistance on specially designed stands simulating the real operating conditions of turbocharger units. The results can be used to analyze the effect of integrated strengthening technologies on wear resistance, considering various parameters such as temperature, torque and operating time.

Key words: turbocharging, rotor, wear bearings, testing, modeling

Introduction

Turbochargers are used in modern engines to increase their performance by increasing the amount of air supplied. However, when operating at high temperatures and rotational speeds, turbocharger assemblies are subject to significant wear and tear, which can affect their long-term operation and reliability. To overcome this challenge and achieve greater wear resistance, researchers and engineers are improving integrated technologies for strengthening turbocharger assemblies.

The purpose of this study is to evaluate and analyze the influence of integrated strengthening technologies on the wear resistance of the turbocharger assembly. Integrated strengthening technologies include the use of new materials, coatings, design changes and manufacturing processes that improve the strength, thermal stability and wear resistance of the turbocharger assembly.

In this study, a comprehensive analysis including experimental tests, mathematical modeling and numerical simulations has been carried out. Analyzed tests of wear resistance on specially designed stands simulating the real operating conditions of turbocharger units. The results can be used to analyze the effect of integrated strengthening technologies on wear resistance, considering various parameters such as temperature, torque and operating time. The results of the above research analysis will help to improve the design and manufacture of turbocharger units, contributing to increase their wear resistance and duration of operation. This can have a significant practical impact on the automotive and aerospace industries where turbocharged engines are used, providing greater reliability and lower maintenance and repair costs.

Analysis of the designs of the turbocharger friction assemblies of modern engines is important for understanding their efficiency and interaction with other engine components. The main components of turbocharger friction include bearings, sealing rings and adjustment mechanisms. Bearings: Bearings play an important role in ensuring smooth rotation of the turbocharger. Two types of bearings are commonly used - rolling and sliding. Rolling bearings, such as ball or roller bearings, provide less friction and wear, but require additional lubrication or cooling. Plain bearings, such as film or hydrodynamic bearings, can handle high loads but have more friction. O-rings provide a seal between the moving parts of the turbocharger, such as the shaft and housing. They prevent air or oil leaks and reduce joint wear. O-rings are usually made of high-strength materials that are resistant to friction and high temperatures. Some modern turbochargers have adjustment mechanisms that ensure optimal performance in different engine operating modes. For example, variable geometries of turbines or compressors allow changing the air flow depending on engine speed. These adjustment mechanisms require precise frictional contacts and are of great importance to the efficiency of the turbocharger.

The analysis of the designs of the friction units of turbochargers of modern engines allows to improve their strength, durability and efficiency. The results of such an analysis can contribute to the further development of turbocharger technologies and the improvement of engine performance.

Basic material

In studies of turbine blades for turbocompressors[1]distinguish two types: guide vanes, which are mounted in the turbine stator, and working vanes, which are fixed on the rotor. Working blades are the most complex in design and have the greatest variety. The design of the working blades can be represented as a complex system consisting of three main parts: the tail, the working part and the head. Each of these parts has a large number of design variations. The working parts of the guides and working blades differ in several features: the shape of the cross-sections and their relative location along the axis of the blade, the presence of overhanging elements over the profiles of the working part, and the way the surfaces are constructed. According to the shape of the sections and their mutual location along the axis, the working parts are divided into parts with a constant profile and a variable profile. Overhangs such as a tail or shelf, or both, may be present over the ends of the working part of the vane, or there may be no overhang. According to this feature, the working parts of the blades are divided into open, semi-open and closed. If the structural element hangs from one end of the blade, for example, from the tail side, and there are no overhanging elements from the side of the head or in the working profile part of the blade, then such designs of blades are classified as blades with a semi-open profile of the working part. Blades with a closed profile have overhanging elements on both ends of the working part. Such blades have a tail hanging over the working part on one side, and a thickening on the other.

According to the described features, there is a wide variety of designs of turbine blades studied in the literature. In order to increase the reliability of small-sized turbochargers used in supercharging systems of auto-tractor diesel engines, a study was conducted[1],the results of which include the following stages.

An original scheme for cooling the bearing of a small turbocharger is proposed and developed. One of the advantages of the scheme is the use of compressed air to cool the bearing. This compressed air is supplied selectively only at critical system operating modes. Local and automatic control of bearing cooling avoids deterioration of overall engine efficiency.

A motorless experiment was conducted to evaluate and confirm the effectiveness of the developed bearing cooling system. The study investigated the effect of excess air pressure in the range of 0.1-0.3 MPa on cooling efficiency. The results of the experiment showed that when using a cooling system with an excess pressure of 0.1 MPa, a reduction in the temperature of the bearing from the critical value of 190 °C to acceptable values of 100-120 °C is achieved after 250 seconds from the moment of coolant supply.

In order to further improve the design of the bearing unit, a mathematical model of the thermal state of the bearing, in particular of the bronze bushing with local cooling, was developed. The results of the motorless experiment were used to refine this mathematical model. As part of the modeling, the boundary conditions of the thermal conductivity problem for surfaces cooled by compressed air were determined.

The conducted study revealed the effectiveness of the proposed cooling scheme of the bearing of a small-sized turbocharger for supercharger systems of auto-tractor diesel engines. The results of the experiments and the developed mathematical models provide grounds for further improvement of the design and implementation of the developed system of automatic regulation of the thermal state of the bearing.

Gas-thermal strengthening methods [2]and restoration of friction parts and assemblies, in particular, plasma spraying, have great potential for the production and repair of aircraft gas turbine engines. Plasma spraying is a universal and technological method that can be used to apply protective coatings to various parts and assemblies. In order to widely use this method in the field of engine construction and repair production, it is necessary to actively work on increasing the range of modern materials resistant to failure that are suitable for plasma spraying. To improve the reliability and operational characteristics of these coatings, it is also necessary to improve the technologies of their application and subsequent processing to ensure the necessary service properties.

The choice of material for plasma spraying and the correspondence of its properties to the technological possibilities of a specific spraying method is a key factor for the successful implementation of gas-thermal methods[3]. Today, a number of enterprises produce various powders for plasma spraying, but information about their composition, properties and purpose is limited, incomplete and outdated. Choosing the most effective and economically feasible coating for a specific part depends on its operating conditions and is a difficult task. The recommendations contained in the literature regarding the selection of coatings "resistant to failure" are not always a sufficient basis for their use in specific conditions, as they are accompanied by clear limitations of the mechanical load parameters.

To assess the performance of gas-thermal coatings in real operating conditions, it is necessary to conduct special tribotechnical tests on installations that simulate the friction modes of real tribocouples. Only after such studies, it is possible to determine the optimal parameters and operating ranges of gas-thermal coatings for specific conditions of friction and load.

In general, the development of new materials for plasma spraying and the study of their properties is an urgent task. In addition, it is important to deepen research on the influence of operating conditions on the performance of gas-thermal coatings, as well as the development of test methods that would ensure the reliable use of such coatings in real conditions.

Turbojet engines (GTDs) have their own characteristics regarding the requirements for lubricants [3]. In comparison with piston engines, in GTE, the lubricant is isolated from the combustion chamber, where the fuel burns. In addition, in the most responsible friction nodes, such as bearings, mainly rolling friction is realized, rather than sliding, which is characteristic of piston engines. The coefficient of rolling friction in GTE is much lower than the coefficient of sliding friction.

In turbojet engines, the turbocharger shaft is well balanced and operates without sudden variable loads at high speeds and significant axial and radial loads. This places special requirements on lubricants, which must ensure stable and effective lubrication of the friction surfaces of the turbocompressor shaft.

Lubricants for turbojet engines must have the following properties:

- high thermal stability, the lubricant must be able to withstand the high temperatures that occur in gas turbines and avoid degradation or oxidation under extreme operating conditions.
- high resistance to oxidation, the lubricant should minimize the formation of deposits and sludge that may occur as a result of oxidation at high temperatures.
- the ability to provide effective lubrication of the turbocharger shaft and other friction components, which reduces heat generation and wear.
- the lubricant should provide stability and minimal wear under high axial and radial loads occurring in the friction nodes.

In Article[4]the question of increasing the durability of the turbocharger by using composite materials is considered. It is noted that some methods of restoring and strengthening parts cannot provide the necessary resource, especially for parts working in abrasive and corrosive environments. Therefore, the use of composite materials becomes a relevant direction for improving the wear resistance and other properties of parts.

The article describes a new method of restoration and strengthening of turbocompressor parts using chemical vapor deposition of metals (CVD - method). This method is based on the decomposition of organometallic compounds. As a result of research, it was established that the developed composite material, obtained using the CVD method, provides an increase in the wear resistance of parts by two to two and a half times compared to new parts. The article also provides a detailed description of the turbocharger, its design and problems associated with its operation. It is noted that the turbocompressor operates in conditions of high rotation frequencies and elevated temperatures of exhaust gases containing chemically aggressive compounds. These factors lead to wear of the turbocharger parts, especially the bearing assembly and the middle housing. The article emphasizes that almost all parts of the turbocharger are subject to wear, and the most damaged part is the middle housing part. The main defects of this part are described, such as wear of the bores under the sleeve, due to crumpling, mechanical abrasion and abrasive wear.

All these facts emphasize the need to develop and implement new ways of restoring and strengthening turbocharger parts in order to increase their durability and wear resistance. The use of composite materials obtained using the CVD method can be one of the effective solutions in this direction. Deposition of coatings by the CVD method is carried out by thermal decomposition of organometallic compounds (MOC). The text states that it is advisable to use chrome coatings obtained by thermal dissociation of chromium hexacarbonyl (Cg(CO)6) in the gas phase to strengthen the parts of the turbocompressor. It is noted that such coatings have a specified microhardness in the range from 12.0 to 20.0 GPa. The conclusions drawn in the text are that the use of the CVD method for the deposition of chrome coatings can significantly increase the wear resistance and durability of turbocharger parts. It is noted that this method makes it possible to obtain a coating with high microhardness, which allows the working surfaces of the bushings to resist abrasive wear.

The paper [5] discusses the importance of turbochargers in modern machines and problems related to the reliability of these units. It is indicated that most modern tractor engines are equipped with turbochargers, but as their prevalence increases, so does reliability, and turbochargers play a significant role in engine failures.

The author notes that a study of the reliability of turbochargers of KamAZ engines showed that these units are among the least reliable units, and the average duration of operation before failure is only 40,000 km. The costs of repairing such units are also significant and amount to about 12% of the cost of engine repair.

It is noted in the work that scientists conducted a lot of research on ensuring and increasing the reliability of machines and units, including turbochargers. However, there are not enough studies on the reliability of turbochargers, so the purpose of this work is to investigate ways to increase the reliability of turbochargers of tractor engines. It is noted that in the city of Dnipro and the region there are several powerful enterprises engaged in the repair of turbochargers, but the main reason for failure of turbochargers is wear and jamming of the bearing assembly. At the same time, the manufacturing quality of domestic turbochargers lags behind American and European manufacturers, and their service life is only up to 700,000 km.

The article also considers the design of turbocharger bearing units and notes that most failures are caused by hydroabrasive wear of bearing unit parts. There is a limit mode of friction, the temperature increases, and the bearing can seize or break. The author emphasizes the possibility of restoration and repair of turbochargers, which allows to significantly reduce repair costs. It is noted that up to 80% of parts can be restored, which helps to reduce the cost of repairs.

This text discusses various methods of restoring turbochargers after repair, including the use of various processing and coating technologies. It is pointed out that many of these methods have disadvantages such as the complexity of the equipment, the high cost and the need for highly skilled workers.

One of the promising directions is the technology of finishing anti-friction non-abrasive processing (FABO), which involves the frictional interaction of the tool with the surface of the part in order to improve run-in and increase wear resistance. Another promising method is epilamation, which involves applying an epilam - a multicomponent system with organofluorine surface-active substances - to the surface of the part.

In work [6] it is indicated that the electrospark treatment method is promising and can be used to increase the post-repair durability of turbocompressors. Studies have shown that the use of electrospark processing with the application of coatings on the surface of the shaft and bushing with involved metals (for example, steel 65G, nickel-bronze-copper) led to a decrease in the coefficient of friction by 15% and an increase in wear resistance by 22%. Studies indicate the expediency of using methods of electrospark treatment, FABO and epilation to increase the reliability of refurbished turbocompressors. However, these methods need further research and optimization in different conditions and regimes.

Electrospark coating is a versatile method that can be used to refinish not only the rotor shaft, but also slide bearings and turbocharger housing parts. It allows you to increase the microhardness of the surfaces of the friction pair and increase their inter-repair service life.

Turbocharging with an additional electrically driven compressor is a promising topology for improving engine performance [7]. At low engine speeds, an electrically driven compressor can achieve a very high compression ratio, as it is designed to increase boost pressure at low engine speeds. This allows you to have a sufficient reserve for flushing resistance at low engine speeds. The electric motor drives only the compressor, which allows you to increase the boost pressure faster. This improves the response of the system to changes in engine load and allows you to quickly gain the required boost pressure. The use of high-tech materials for the manufacture of the compressor rotor allows to reduce its inertia. Since the electrically driven compressor is not connected to the turbine, it does not need high heat resistance, which allows the use of lighter materials. Turbocharging with an additional electrically driven compressor has great potential to improve transient response at low engine speeds. This system allows for better sustained power at low engine speeds. However, an electrically driven compressor cannot be used at high engine speeds due to the limited range of mass flow. The disadvantage of this system is the need to generate all the electrical energy to power the electrically driven compressor through a generator or alternator that runs from the engine shaft. An electrically driven compressor is usually smaller in size compared to a turbocharger because its main function is to increase boost pressure at low engine speeds with a sufficient margin of washout resistance.

The turbocharger bearing system [8] must hold the rotor in a given position and thus must withstand the rotor forces that occur during turbocharger operation. Therefore, its components must be designed taking into account the expected loads on the bearings. The design of the bearing system used also has a significant effect on the overall efficiency of the turbocharger and the performance of the internal combustion engine. It should perfectly match the trade-off between bearing friction and load capacity. For example, the attainable low end torque of an engine is reduced if the bearing system creates more frictional losses than is inherently necessary for safe and durable operation, as most of the available turbine power must be used to compensate for bearing losses instead of providing boost pressure. . In addition, the transient speed of the turbocharger rotor can also be compromised, and therefore the response of the turbocharged internal combustion engine to the load step becomes less efficient than it could be. Apart from the radial bearings, the thrust bearing is a component that needs some attention. This can already account for approximately 30% of the total bearing friction, even when no load is applied, and this fraction increases even more under thrust loads. It must withstand the net thrust load of the rotor under all operating conditions, which is the result of the superimposed aerodynamic forces created by the compressor and the turbine wheel. The problem for determining the thrust forces arising on the engine is the non-stationary load under pulsation conditions. Conducted experimental studies of the axial movement of the rotor, as well as changes in thrust force under engine operating conditions, using a specially prepared compressor lock nut in combination with an eddy current sensor. The second derivative of this signal can be used to estimate changes in traction force. In addition, a modified thrust bearing equipped with strain gauges was used to cross-validate the results of the position measurement and the traction force simulation. All experimental results are compared with an analytical model of the thrust force, which is based on simultaneously measured pressure signals determined by the crankshaft angle, before and after the compressor and turbine stages. The results provide insight into axial turbocharger rotor oscillations occurring during the engine cycle for several engine operating moments. In addition, they allow us to judge the accuracy of thrust modeling approaches that are based on measured pressures.

The stability of the turbocharger rotor is governed by a combination of rotor dynamics and fluid dynamics [9], as the high-speed rotor system is supported by a pair of hydrodynamic floating ring bearings consisting of inner and outer fluid films connected in series. To investigate the stability, this paper develops a finite element model of the rotor system taking into account the exciting forces such as rotor unbalance, fluid hydrodynamic forces, lubricant supply pressure, and self-weight. Dimensionless analytical expression of nonlinear oil film forces in floating ring bearings was obtained based on the theory of short bearings. On the basis of numerical modeling, the impact of rotor imbalance, oil viscosity, oil supply pressure, and bearing clearances on the stability of the rotor system of the turbocompressor was studied in [9]. Disciplines of stability of two films and dynamic characteristics of the rotor system are given.

The thermal state of the sliding bearings has a great influence when calculating the dynamics of the flexible rotor of the turbocharger. Experimental studies have shown that the temperature difference between the turbine and compressor bearings can reach twenty degrees. In addition, the temperature is unevenly distributed over the lubricant layer. It intensifies in the zone of increased pressure. The task of assessing the thermal condition of rotor sliding bearings is relevant. In [10], the effect of eccentricity on the pressure distribution in a thin lubricating layer of a non-Newtonian fluid is considered. The distribution of temperatures and pressures in the lubricant layer is constructed taking into account the rheological properties of the lubricant. The boundary conditions that were used to solve the problem were taken from the experiment. The results will be used to solve the problem of turbocharger rotor dynamics.

The objectives of the study [11] were to develop a dynamic model for rotary ball bearing systems of a turbocharger, to correlate the simulated shaft motion with experimental results, and to analyze the corresponding bearing dynamics. The high-speed turbocharger test stand was designed and developed to measure the dynamic response of the rotor under various operating conditions. Displacement sensors were used to register the movement of the shaft in the range of operating speeds. To achieve the objectives of the analytical study, a discrete element radial thrust ball bearing model was coupled with an explicit finite element shaft to simulate the dynamics of a turbocharger test bench. A bearing cartridge consists of a common outer ring, a pair of split inner rings, and a row of balls at each end of the cartridge. The rotor is modeled using the finite element method. The cartridge and rotor models are coupled in such a way that the motion of the flexible rotor is transmitted to the inner rings of the cartridge with corresponding reaction forces and moments from the bearings applied to the rotor. The rotor model was used to investigate the shaft motion and bearing dynamics as the system crosses critical speeds. A comparison of the analytical and experimental shaft motion results resulted in minimal correlation, but showed similarity across critical speeds.

The publication [12] presents the possibility of extending the service life of the sealing ring of the rotor shaft in an automotive turbocharger using an Al-Fe intermetallic alloy. The complex results of tribological, metallographic and profilometric tests of this alloy on the T-05 stand made it possible to present a real friction node. Based on empirical tests, it will be possible to determine which alloy (Al-Fe alloy or the one currently used for automotive turbocharger rotor shaft sealing rings) has better tribological properties. For this purpose, the study was based on an experiment that involves three main factors determining the wear of the studied association. The result of the experimental plan was obtaining three-dimensional diagrams showing the influence of wear factors on the friction force and surface topography.

In Article[13]the results of studies of turbocharger shaft bearings under different lubrication regimes (dry friction and lubrication with different types of oils) are given. In particular, the wear of the surface of the turbocharger shaft was evaluated. One of the most frequent breakdowns is the jamming of the turbocharger shaft in the sliding bearing, which causes it to rotate, which leads to the destruction of the unit and expensive repairs. Based on the tests, it was established that the average value of the representative fracture surface on the turbocompressor shaft is reduced with the help of less viscous soil. A similar situation was observed when new oil was used instead of processed oil - this affected the value of the diameter of the cracks.

The journal and thrust bearing design process remains a key aspect in the development of the center section of an automotive turbocharger. The rotor assembly must be supported both radially and axially, ensuring safe operation with extended service life. Both types of bearings must be designed with many limitations in mind. Housing bearings are designed with an emphasis on shifting unwanted critical frequencies beyond the operating range while supporting various types of non-linear oscillations. Thrust bearings are configured to provide a balanced ratio of load capacity and frictional losses. In general, during design, both types of bearings are treated as two different entities, even if they work with the same central section. At work[14]the cross influence of trunnions and thrust bearings during the design process of thrust bearing pads is investigated. It is carried out by taking into account the interaction of thrust and support bearings during transient nonlinear acceleration simulation. The main attention is paid to the designs of pads with different geometric dimensions, which, based on stationary calculations, have almost the same load properties and friction losses. It is shown that thrust bearings consisting of such pads do not necessarily have the same effect on the nonlinear vibrations of the rotor unit during start-ups. The interaction of the abutment and the support of the support leads to transient hydrodynamic properties of the pad that no longer correspond to steady-state predictions. It is shown that thrust bearings equipped with geometrically identical linings, but differently located around the circle, interact with the rotor assembly differently depending on the nature of the radial bearing. A floating plain bearing in combination with a thrust bearing with symmetrical or asymmetrical pad distribution can have a positive or negative effect on shaft movement and load capacity.

The turbocharger is characterized by low weight and a high-speed rotor that reaches a rotation speed of up to 350 rpm. To withstand these extremely high rotational speeds, the shaft is usually supported by floating ring bearings, resulting in complex rotor dynamics. The work [15] summarizes the dynamics of the rotor of automotive turbochargers, presents its expected general behavior along with a review of the literature on the most important topics related to the dynamic analysis of the turbocharger. The non-linear effect of a floating ring bearing on shaft lateral vibration is discussed, as well as the effect of various bearing systems on turbocharger response, including the effect of a thrust bearing on axial and transverse rotor dynamics. Current studies on turbocharger modeling and research are also presented. Most of the work relies on the development of high-accuracy, low-computational models, including several different effects, such as temperature fluctuations and mass-conserving cavitation algorithms in lubricated bearings, research into new floating ring and thrust bearing geometries, and optimal solutions to reduce friction loss. er- or understated.

Modern turbochargers are high-speed rotating devices, usually supported by fully floating or semi-floating bearings. Depending on the size and operating speed of the turbocharger, the dynamics of the rotor changes significantly. Industrial turbochargers operate at frequencies below 20,000 rpm and their rotor weight is significant, resulting in quasi-linear rotor dynamics. In contrast, automotive turbochargers rotate at up to 300,000 rpm with non-linear dynamic rotor characteristics. Because of this nonlinearity, the rotor movement is intense, and the load on the bearing changes dynamically all the time. The consequence of this is a reduction in the service life of the turbocharger. At work[16]the effects of changing bearing clearances are described, as well as the differences between semi-floating and fully floating bearing designs based on journal articles and scientific publications on the subject. In addition, the phenomenon of damping and vorticity within the bearing system will be investigated and presented in a comprehensive literature review of automotive turbocharger rotor dynamics.

A promising solution for increasing the specific power of motor-tractor equipment is turbocharging, which allows to increase the power by up to 50%. At the same time, a significant increase in speed, load and temperature regimes leads to a significant increase in the number of failures and a decrease in reliability by 2-3 times. In Article[17] Voltheoretical and experimental studies have established that the temperature of the bearing and oil at the turbocharger drain changes under the influence of the oil temperature at the entrance to the rotor bearing, the frequency of rotation of the rotor shaft and changes in the oil pressure at the entrance to the . bearing. This allows you to set the performance limits of the bearing in extreme operating conditions. Installation of an autonomous lubrication and braking device maintains the required level of reliability and increases reliability. The hydraulic accumulator, installed in the lubrication system of the regular part of the engine turbocharger, lubricates and cools the rotor bearings when the engine crankshaft speed drops. The built-in braking device reduces the idle time of the rotor and thereby prevents oil starvation and dry friction of the rotor bearing. The joint use of a hydraulic accumulator and a braking device minimizes the risk of dry friction and accidental failure of the turbocharger. It has been proven that the rotor braking device, built into the engine intake system, with the calculated design parameters, reduces the time of rotor exposure by 30-35%. This reduces the dimensions and operating time of the hydraulic accumulator and at the same time eliminates jumps in the compressor section and any damage to its parts. In these conditions, the development of independent bearing lubrication systems and their replenishment with the help of built-in hydraulic accumulators during start-up, significant loads at minimum crankshaft rotation frequencies and engine shutdown is relevant.

In Article[18]an analysis of tribological research is provided regarding the most promising method of restoring the primary resource of engines using gas-dynamic spraying. It was established that to reduce the coefficient of friction and increase the wear resistance of the coating, the use of copper-zinc powders of the C-01-11 brand, applied by the method of gas-dynamic spraying, is theoretically justified. It was established that the physical and mechanical properties of the coatings (roughness, microhardness, friction coefficient) on the restored turbocharger meet the manufacturer's requirements. The coefficient of friction in the connection of the rotor shaft (reduced copper and zinc powder) with the sliding bearing (from tin-lead bronze Bros - 10 - 10) is 20% less than in the connection where the rotor shaft is made of steel 40. The total wear of a bearing unit with a restored gas-dynamic sprayed rotor shaft is 20% less than in a unit where the rotor shaft is restored according to the basic technology. The technology of restoring the surface of the turbocharger rotor shaft under the sliding bearing (gas dynamic spraying) has been developed, which increases its resource by 23% compared to the basic technology of repairing the rotor shaft. . This makes it possible to increase its operating time with the established regulatory and technical documentation for overhaul of the engine. A stand for testing diesel turbochargers with recuperation technology has been developed, which allows determining the parameters and characteristics of diesel turbochargers in different periods of operation, break-in and adjustment. Bench tests have shown that turbochargers with reconditioned rotor shafts using the proposed technology increase overall performance by 13% more after 2,000 hours of operation than turbochargers repaired using the basic technology. Operational tests have shown that turbochargers repaired using the proposed technology have a working life of 989 moto-hours more than turbochargers repaired according to the existing technology.

Conclusion

A comprehensive analysis was carried out, including experimental tests, mathematical modeling and numerical simulations. Analyzed tests of wear resistance on specially designed stands simulating the real operating conditions of turbocharger units. The results can be used to analyze the effect of integrated strengthening technologies on wear resistance, considering various parameters such as temperature, torque and operating time.

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Фасоля В., Гетьман М., Старий А. Аналіз працездатності пар тертя ротора турбокомпресора автомобільного двигуна.

Турбокомпресори використовуються в сучасних двигунах для підвищення їх продуктивності шляхом збільшення кількості поданого повітря. Для підвищення зносостійкості дослідники і інженери вдосконалюють інтегровані технології зміцнення вузлів турбокомпресора. Метою даного дослідження є оцінка та аналіз впливу інтегрованих технологій зміцнення на зносостійкість вузла турбокомпресора. Інтегровані технології зміцнення включають в себе застосування нових матеріалів, покриттів, конструкційних змін та процесів виготовлення, які покращують міцність, термічну стійкість та зносостійкість вузла турбокомпресора. Проведений комплексний аналіз, включаючи експериментальні випробування, математичне моделювання та числові симуляції. Проаналізовані випробування зносостійкості на спеціально розроблених стендах, що моделюють реальні умови роботи вузлів турбокомпресора. Результати можуть бути використані для аналізу впливу інтегрованих технологій зміцнення на зносостійкість, враховуючи різні параметри, такі як температура, обертовий момент і час роботи.

Ключові слова: турбонаддув, ротор, підшипники зношування, випробування, моделювання

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Justification of the effect of the regularities of the flow of nanotribological processes in the materials of joint parts on the increase of wear resistance, reliability and efficiency of the functioning of machines and mechanisms

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Abstract

The article elucidates the essence of nanotribological processes in the materials of conjugation of samples of parts by the methods of the surface force apparatus, scanning tunneling and atomic force microscopy. The substantiation of the mechanisms of their occurrence is given by the methods of molecular dynamics and classical contact mechanics. Attention is paid to dry adhesive and contactless dynamic friction of conjugated samples, physical processes in "sticking-sliding" tribocontacts, adhesive effects, etc. The values of the lateral and normal forces acting on the probe were analyzed. The probe was considered as a collection of point particles of concentrated mass with a multiatomic structure of the material. The contact and movement of the probe with the surface of the sample was considered in the "probe-surface" system with minimal potential energy and lateral load and taking into account conservative and dissipative forces.

The effect of "sticking-sliding" is substantiated with the help of the apparatus of surface forces. The atomic periodicity of the effect is explained on the basis of the model of the formation and breaking of adhesive bonds and the "atom-magnet" model. It is shown that the patterns of "sticking-sliding" processes can be determined by using the parameters of shear stress and specific work of adhesion.

It is advisable to use the Johnson-Kendall-Roberts theory to explain the elastic adhesive contacts, and the Deryagin-Mullier-Toporov theory for the residual friction force and probe separation force.

It is shown that there is a significant connection between friction and adhesion processes. The correlation between the macroscopic value of the surface energy of materials and their shear modulus for homogeneous contacts was determined.

On the basis of adhesive effects and the effect of "sticking-sliding", it is possible to control frictional forces and create favorable conditions for their absence, which gives grounds for obtaining high wear resistance of tribo-joints of parts, their reliability and maximum efficiency of the functioning of machines and mechanisms.

Key words: adhesive effects, sticking-sliding, conjugated surfaces, lateral forces, friction, wear resistance, reliability, efficiency.

Introduction

The study of the physical nature of the processes of friction and wear at the atomic level of the materials of the joint parts became possible after the creation of atomic force microscopes. The intensive development of this technique led to the formation of nanotribology, which combined experimental and theoretical studies of adhesion, friction, wear, lubrication, chemical activity and triboelectromagnetism at the nanostructural level. As a rule, the problems associated with friction are mostly engineering in nature and are considered physics with macroscopic contacts of mating surfaces of parts contaminated by the presence of adsorbed particles, wear products, and lubricants [1].

The stimulus for the development of nanotribology is considered to be a fundamental understanding of the role of a set of microcontacts that occur when the surfaces of tribocoupled parts are in contact. At the same time, the total area of actual contacts may be significantly less than theoretical estimates [2].

Level approach in tribology [1-3] shows that the phenomena and processes in the contact area of tribojunctions of samples and parts are studied at the macro-, meso-, micro- and nano-levels. With the transition to a qualitatively new nanolevel of research, it was found that the physical processes in tribocontacts are much richer and more diverse and include many new phenomena: phase transitions due to the shear arrangement of thin films in the "probe-part surface" contact; the formation of contact "jumpers"; chemical, electrochemical and triboelectric effects; effects related to humidity, superconductivity, etc.

Literature review

An important place in the study of nanotriboeffects is occupied by questions that are considered using the methods of the surface forces apparatus and the quartz crystal microbalance technique. These methods are currently the most promising for nanotribology. To them can be added methods of surface nanoindentation technique, methods of scanning tunneling microscopy and atomic force microscopy [4-7].

The study of friction processes at the nanostructural level is of considerable interest for a wide range of technical applications: the technology of production and surface coating of hard magnetic disks for computers; production of microsensor sensors, etc. Engineering applications of tribology and tribotechnics in mechanical engineering require a deeper understanding of the tribological properties and characteristics of materials at the atomic level in order to optimize and predict the tribotechnical characteristics of joint parts. The successful solution of these tasks requires the reduction of the existing gap between the macro-, meso-, micro- and nanostructural levels of research on the materials of tribojunctions of samples and details of machines and mechanisms.

Adequate theoretical description of many experimentally detected tribophysical effects continues to be unsatisfactory, despite the fact that recently a number of important results were recorded, which were predicted and interpreted using the method of molecular dynamics and classical contact mechanics [8,9]. The mode of dry friction at the macroscopic level does not depend on the visible contact area and practically does not depend on the sliding speed. At that time, it is caused by a complex variety of surface properties, the presence of numerous microcontact zones, adhesive and deformation effects, as well as "ploughing" of the surface with microroughnesses and wear products [10,11]. To understand the nature of the most complex and least studied mechanism of adhesive friction, it is advisable to use a level approach in tribology.

One of the sub-levels of the nano-level is related to the need to build a detailed atomistic theory of triboprocesses, which describes the processes of adhesion, friction and wear within the framework of atomistic models of chemical bonding and elementary electron-phonon processes, which lead to energy dissipation in the surface layers of tribocoupled materials of samples and details [12].

Another sublevel of the nanolevel concerns the nature of the sliding mechanism, in which it is not clear whether the relative movement of the touching surfaces is continuous or consists of a series of discrete acts of sticking and sliding processes. The implementation of the latter processes requires the detection of the scale of distances and the time interval corresponding to elementary microslip. Experimental studies indicate that the sticking-slip processes are characterized by the periodicity of the material lattice, allowing to obtain the atomic contrast of the surface in the lateral contact mode of atomic force microscopy [1 3,14]. Note that this is possible only in the case of atomically smooth surface conjugations. Much more often, the contact area is contaminated by the presence of adsorbed substances and wear products.

The analysis of experimental and theoretical results obtained in the field of nanotribology in recent years is highlighted in the works of the following foreign authors [11-14]. It can be seen that an attempt is being made to construct some integral physical picture that is specific to nanotribocontacts as elementary friction zones. It should be noted that the results presented in the literature review were practically not discussed, and attempts to systematize theoretical ideas are fragmentary due to the fact that the main calculation models are in the stage of development and evaluation. Nanotribological adhesion-sliding processes based on models of adhesive friction forces and dynamic mechanisms of non-contact friction also require substantiation.

During the discussion of theoretical models of the tribon nanolevel in works [15, 16], much attention is paid to the problem of dry adhesive and contactless dynamic friction in a vacuum. At the same time, elementary processes are in the field of attention, the understanding of which brings researchers closer to the understanding of the nature of friction as a whole. Theoretical justifications of the effect of "plowing", wet friction, thermodynamic aspects of nanotribology and a number of other issues that require special consideration are considered in detail in literary sources.

This is a brief description of the main modes of operation of atomic force microscopy and other methods used in experimental research of micro- and nanocontacts [17,18]. Physical processes in tribocontacts, such as "sticking-sliding", adhesive, chemical and others, are discussed on the basis of available experimental material. At the same time, the existing theoretical concepts that allow the interpretation of these experimental data are considered.

The approximation of classical contact mechanics in the interpretation of atomic force microscopy data on "dry" adhesive friction in a vacuum is discussed. Simple models of the lateral movement of the probe are considered, which allow the interpretation of experimental images of the investigated surfaces of samples and parts. A detailed analysis of the evolution of the nanocontact structure using the molecular dynamics method is carried out. The mechanisms of static and dynamic friction are considered, the application of theoretical models is analyzed to explain the experimental dependence of the friction force on the load force, adhesion-sliding processes, interpretation of the damping effect of the motion of adsorbed films in experimental studies with a quartz microbalance [19,20].

The interaction of the tribodiagnostics probe and the surfaces of samples and parts allows not only to diagnose the structure of the contact zone on an atomic scale, but also to modify some properties of the conjugated surfaces.

It was revealed [21,22], to reduce the time of contact scanning of the technological process, it is necessary to increase the scanning speed to 1 cm/s It is noted that scanning probe microscopy, nanotribology and nanotechnology can lead to significant changes in mechanical engineering.

Purpose

The purpose of this work is to find out the influence of nanotribological processes occurring in the materials of conjugated samples of parts on their wear resistance, reliability and efficiency of the functioning of machines and mechanisms.

Results

Investigating the physical processes in the nanotribocontacts of the conjugated surfaces of the sample parts, we will focus on the theoretical justification of various experimentally observed phenomena. Among which the "sticking-sliding" effect is the key effect for the contact mode of atomic force microscopy. For the first time, the effect was observed at the atomic level when measuring the lateral forces acting on a tungsten probe sliding over the surface of highly oriented pyrolytic graphite. Similar measurements were carried out on a wide range of contacting materials from soft to hard.

Comparative studies of the "sticking-sliding" effect were conducted under the leadership of Fujisawa [2,3] for various combinations of probe and sample materials. At the same time, the observed periodicity of the sliding of the probe on the surface of the sample corresponded to the topography of the atomic relief of the surface itself, obtained in the normal mode of atomic force microscopy. At the same time, the positions of the maxima of the lateral and normal forces were slightly shifted relative to each other. The observed periodicity of the lateral interaction is believed to be responsible for all the observed contrast, including topographic images in the normal mode. The effect of "sticking-sliding" is revealed in experimental studies with the apparatus of surface forces [11,12]. The transition to continuous sliding without wear is observed at significantly higher speeds. At the same time, the question of the effect of the observed "sticking-sliding" periodicity on the fact that the atoms of the probe relax into a structure comparable to the atoms of the sample should be clarified. It was found that even for probes with a disordered atomic structure, periodicity of lateral forces is observed, which corresponds to the translational symmetry of the sample material. In a typical experimental situation, as a rule, there is both lateral and longitudinal deformation of the cantilever, but the latter deformation can also be caused by a change in the normal force. It was found that there is always a connection between the corresponding signals in the lateral and normal modes. If this connection is not controlled, then the measurement results are distorted.

Schematically, the principle of measuring the investigated surface by atomic force microscopy is shown in fig. 1.

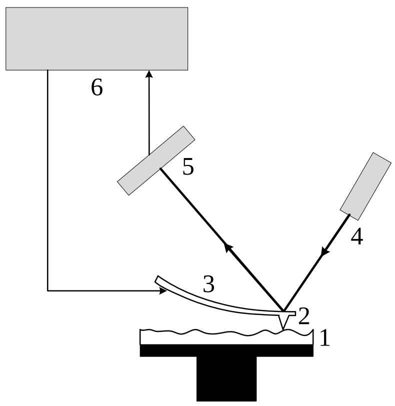

Fig. 1. Block diagram of the principle of measurement of the examined surface in an atomic force microscope: 1 – the examined surface of the sample; 2 – probe (probe); 3 – cantilever; 4 – laser beam; 5 – photodiode; 6 – electronic conversion and feedback device

In an atomic force microscope, a thin probe (2) located at the end of a cantilever beam (3), known as a cantilever, scans the surface (3). High-precision movement of the probe is carried out with the help of piezoelectric elements that change their length under the influence of voltage. When driving over an uneven surface, the dipstick rises and falls. These very small vertical movements are detected with the help of a laser beam (4), which is reflected from the upper surface of the cantilever equipped with a mirror. Even with small displacements, the beam undergoes a large deviation, which can be measured by a matrix photodetector (5).

The received signal is analyzed using an electronic device (6) and converted into an image of the surface of the sample. An electronic feedback mechanism is used to ensure a constant force between the sample surface and the probe and to prevent possible damage.

Knowing the role of the atomic structure in the relative movement of contacting surfaces, researchers tried to explain the "sticking-sliding" effect based on the modernized classical ideas of Tomlinson and the method of molecular dynamics [24]. Since modern models of probes are considered as a collection of point particles with a concentrated mass that has no internal degrees of freedom, or taking into account a multiatomic structure, the visual picture of the "sticking-sliding" effect is significantly simplified.

Initially, the probe is at the minimum point of the potential energy of the "probe-surface" system. This interaction is characterized by a periodic potential that reflects the translational symmetry of the atomic structure of the surface of the part. An essential feature of this model is the assumption of the possibility of applying adiabatic conditions at each step of the probe's movement. In lateral contact loading caused by cantilever scanning, energy is stored in the form of elastic energy of the cantilever-specimen contact. The relative sliding of the probe on the surface of the part sample begins at the moment when the accumulated energy in the material is large enough for the probe to jump out of the potential well and be fixed at another point on the surface. After that, the system relaxes and excess energy quickly dissipates from the contact area through the electron-phonon subsystem. Note that a very short dissipation time is observed, since the characteristic velocities of electrons and phonons (10^{-7} - 10^{-4} m/s) are many orders of magnitude higher than the typical scanning speeds of an atomic force microscopy probe.

Studies show that in order to observe the instability associated with the "sticking-sliding" effect, it is necessary to combine a "soft" cantilever with a "hard" surface of the part sample under the condition of strong interaction. Moreover, more energy dissipates in the case of softer contacts. At that time, the models did not take into account possible mechanisms of energy dissipation, in which the frictional force is proportional to the speed.

It should also be noted that the oscillatory model of the "probe-surface" system describes this "sticking-sliding" effect only under the condition of critical damping of the cantilever, which is its significant drawback due to the high elasticity of the cantilever. To eliminate this contradiction, Johnson and Woodhouse [25] took into account the elastic stiffness of the contact and found a relationship between the effective stiffness of the "probe-surface" system and the amplitude of the periodic friction force. The weakest point of this rationale is the discrepancy between the point oscillator model and the actual situation with the atomic force microscopy probe. The experimental fact is that the period associated with the "stick-slip" effect coincides with the period of the surface atomic structure. In the mode of contact lateral mode of atomic force microscopy, it is possible to talk not about the actual atomic rarefaction of the surface of the part, as is the case in the modulation mode, but about the atomic contrast. This is evidenced by the fact that there is no rarefaction of point atomic surface defects in the contact mode.

Molecular dynamics calculations also indicate the presence of the "sticking-sliding" effect and friction without wear at low loads. A decrease in the friction force is observed when the scanning speed increases. The most serious objections related to the results of molecular dynamics calculations related to the interpretation of the "sticking-sliding" effect. Their range of speeds (1-2000 m/s) causes them, which exceeds scanning speeds in atomic force microscopy. At that time, numerical molecular dynamics experiments significantly enrich the understanding of structural changes occurring in the contact zone.

At the same time, clear differences between conservative and dissipative lateral forces acting on the probe should be taken into account. During the movement of the probe corresponding to the friction loop, we are dealing with the maxima of the static force at which the probe begins to slide. When the real atomic structure of the contact zone is unknown, there is no possibility to detect the movement of atoms inside it. It is believed that there will be limited sliding of atoms on the periphery of the contact. This happens even with very small lateral forces. It was found that the observed lateral force cannot be attributed completely to either dissipative or conservative. It contains both of these components.

The lateral contrast recorded when the direction of movement of the probe is reversed is not unusual, since the contrast does not directly show the atomic structure. If the probe is in the extreme right position, the system is already ready for micro-sliding. The system does not care whether the probe continues to move to the right or changes direction to the opposite. In both cases, the force modulus further decreases. As a result, after a sharp decrease in the initial phase of the reverse movement of the probe, the lateral force turns out to be close to zero and the "probe-surface" contact is unloaded. After that, a new growth of the lateral force (modulo) begins, which continues until the beginning of the next sliding cycle. This indicates that sharp changes in the lateral force are irreversible and are associated with the dissipative nature of the sliding process in the triboconjugates of the "probe-sample of parts".

The atomic periodicity of the "sticking-sliding" effect can be qualitatively explained by the model of the formation and breaking of adhesive bonds. At each position of the probe on the surface of the part sample, the contact spot covers a certain part of it. Moreover, for a spot of a given shape, the number of surface atoms under it varies depending on the lateral coordinates with the lattice period of the surface material. If the probe is located in relation to the surface of the part sample at a point corresponding to the minimum number of adhesive bonds near the boundaries of the contact patch, then during its sharp micro-slip the dissipative force of friction will be minimal, due to the fact that the number of broken and newly created adhesive bonds is relatively small Small discrete jumps and a fine structure of the lateral force are not accompanied by a loss of stability of the triboconjugation of the "probe-sample parts" that continue to accumulate energy. In the position that corresponds to the maximum number of bonds along the boundaries of the contact spot, their rupture as a result of microslipping with a subsequent sharp drop in the lateral force on the cantilever becomes catastrophic. At this moment, the probe breaks off. Old adhesive bonds behind the contact spot are broken, reducing the resistance to the translational movement of the probe, and new ones arising in front of the contact spot capture it forward. The nature of this movement can be described by the model of "atoms-magnets", which are arranged on the surface in the form of a regular lattice and have a vertical degree of freedom, and the probe, which has a flat shape, is installed on a pendulum suspension, the axis of which moves with a constant horizontal speed. This model allows you to visually visualize the atomic "sticking-sliding" effect at the macro level.

Adhesion effects are of significant importance in the problem of nanotribology (atomic friction), as they determine the contact area and interaction of sample parts, as well as their interaction with the probe. Adhesion forces can be directly measured by atomic force microscopy using the lead-pull mode of the probe, or by measurements of friction force-load force relationships.

If contact mechanics is used to substantiate the obtained data, then two main parameters can be used to substantiate the regularities of the "sticking-sliding" processes: shear stress and work of adhesion. The shear stress is proportional to the critical lateral force that causes the probe to slide in the "stick-slide" mode. The work of adhesion is equal to the specific energy related to the unit of tribojunction contact area of the "probe-sample of parts" required for its rupture:

$$\gamma = \gamma_1 + \gamma_2 - \gamma_{12}, \tag{1}$$

where $\gamma_1, \gamma_2, \gamma_{12}$ are the specific surface energies of the probe, the part sample, and the interfacial energy of their contact, respectively.

Let's consider questions related to the dependence of the specified values on the atomic structure of the contact, temperature, external pressure, chemical composition, and the material of the part sample. But at the same time, we take into account the differences between model representations of "dry" vacuum conditions and the more complex case of a "wet" surface, when intermolecular forces can change significantly due to the presence of solvent or solute molecules.

In the case of "dry" friction, the work of adhesion is determined by the separation force of the atomic force microscopy probe from the surface of the part sample. The pull-off force, which is negative in sign, corresponds to the force applied to the cantilever required to separate the surfaces. In the theory of Johnson-Kendall-Roberts [12] for elastic adhesive contacts of soft materials and a probe of a parabolic profile with a radius of curvature R_z , the separation force is equal to:

$$F_{sep} = -1{,}5\pi R_z \gamma . \tag{2}$$

Characteristic of the Johnson-Kendall-Roberts theory is that it describes the elastic contact of materials with a strong short-term (attractive) adhesive interaction. The contact of rigid materials with long-range attraction is better described by the Deryagin-Mullier-Toporov theory [11], and the numerical coefficient in expression (2) can be replaced with 1.5 by 2.

In the Johnson-Kendall-Roberts approximation, the ratio for the residual friction force F_{res} at the critical point of probe separation and work of adhesion is:

$$F_{res} = \pi\tau \left(\frac{9\pi R_z^2 \gamma}{8E_{coc}} \right)^{2/3}, \tag{3}$$

where τ is the shear stress, $E_{coc} = (1-\eta_1)/E_1 + (1-\eta_2)/E_2, E_{1,2}$ is the composite modulus of elasticity of the tribocoupled components of the probe materials and sample parts. In the Deryagin-Mullier-Toporov theory $F_{res} = 0$, the separation force corresponds to the van der Waals force of gravity, and for the contact of a spherical probe with a flat surface, we have:

$$F_{sep} = \frac{H_G R_z}{6h_{sep}^2}, \tag{4}$$

where H_G - became Hamakera, R_z – probe radius, h_{sep} – the distance between the probe and the surface of the sample (parts) at the time of separation. Typical values of h_{sep} lie within 0.2...0.3 nm, and constant H_G – in the range of 0.6...2 5 eV.

It was found that friction and adhesion processes are sensitive to changes in the structure of tribocouple materials and chemical interactions in the contact zone. This behavior takes place regardless of changes in the shape of the probe. The peculiarities of the mentioned processes can be explained by chemical or structural changes in the contact zone induced by the scanning of the probe. It is assumed that similar changes in friction and adhesion can be caused by a change in the nature of the proportionality of the probe materials and samples of details of the contacting surface structures.

The weak dependence of the shear stress on the value of the work of adhesion is unusual, since most often there is a linear proportional relationship between these values, in the absence of wear. The simplest model explaining this dependence is the "cobblestone" model, which is equivalent to Tomlinson's model [24]. The sliding of contacting surfaces should be considered similarly to the rolling of a wheel. At rest, the wheel falls into the depression formed by the paving stones, so in order to set it in motion, it is necessary to apply a lateral force sufficient for the wheel to get out of the hole. In this model, the role of surface attractive forces is played by gravity. For an atomically smooth surface, cobblestones correspond to atoms. A similar picture will be for the contact structure of the parts samples. Experimental studies performed on "sticking-sliding" on surfaces, layers of liquid molecules, confirm this model. It was also found that for systems of chain molecules, the work of adhesion increases in the case when conjugated surfaces are in contact with each other. There is also a hysteresis of the contact area during the approach and separation of the mating surfaces, and the friction force increases with an increase in the contact area.

The relationship between the processes of friction and adhesion determined by the internal molecular structure was determined. For dry tribocontacts of materials, adhesive and frictional hysteresis should not be observed [1,26]. There is a model that establishes the relationship between shear stress and adhesion work (in the case of dry contacts). The correlation between the macroscopic values of the surface energy of materials and their shear modulus per atomic radius for homogeneous contacts was determined (Fig. 2).

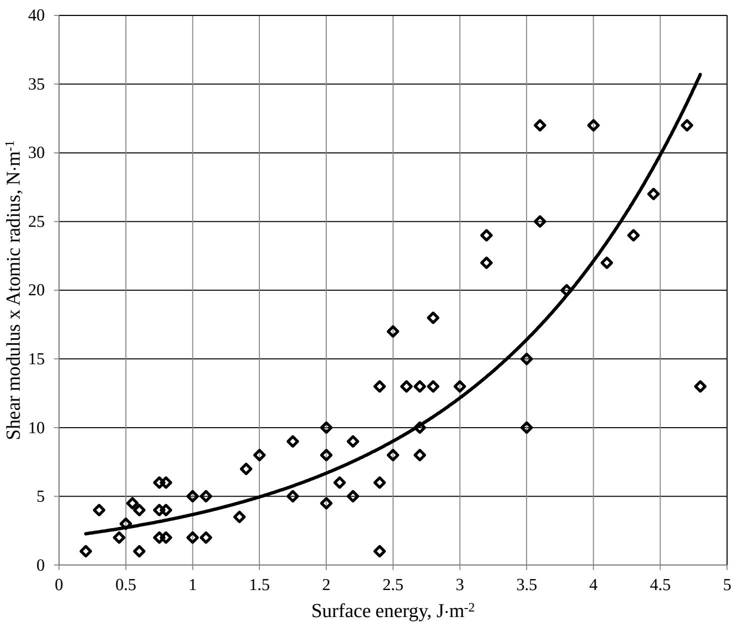

Fig. 2. Correlation between the value of the macroscopic shear modulus per atomic radius and the surface energy of homogeneous contact materials

Since the shear modulus is directly proportional to the shear stress, it can be assumed that the values of G and τ change in a consistent manner. Figure 2 shows equally the correlation between the values τ and γ. This correlation shows that it is possible to distinguish two groups of materials with different proportionality coefficients between τ and γ, due to a non-linear dependence. In this case, it is close to quadratic: $\tau \approx \gamma^2$. The results of the research claim that special attention should be paid to the comparative comparison of the value of the work of adhesion, which is measured using the atomic force microscopy method, with the expected macroscopic values of this value, and a similar comparison for the shear stress values.

In order to obtain the observed extremely low values of the work of adhesion, it is possible to assume in accordance with formula (1) that the equality holds:

$$\gamma_{12} = \gamma_1 + \gamma_2 . \tag{5}$$

High values of γ_{12}, in turn, should indicate a very strong rearrangement of the atomic structure of the interphase boundary, which is unlikely in the case of contacts of solid materials. For the contact of conjugates of samples of parts from homogeneous materials, we have $\gamma_{12} = 0$.

The assumption that the order of magnitude of the macroscopic characteristics of materials when moving to the nanoscale is preserved is not entirely obvious. This follows from the analysis of values of work of adhesion in experimental studies. Much more complex adhesive effects are observed in the case of "wet" tribocontacts. It should be noted that the measurements were carried out in the "input-outlet" modes. The application of atomic force microscopy methods and techniques in this case is particularly promising. At that time, the observed solvation forces require further research.

In the process of experimental research, a linear correlation was found between the macroscopic values of the surface energy, which is measured by the marginal wetting angle, and the friction forces. Due to the small size of the contact zone of the atomic force microscopy probe with the surface, quantization of adhesive forces was detected. The probability of locating the probe at a distance s from the surface of the sample has the character of the Boltzmann distribution:

$$p(S) \sim \exp\left[-\frac{W_P(s)}{k_B T}\right], \tag{6}$$

where $W_P(s)$ is the potential energy, k_B and T is the Boltzmann constant and the thermodynamic temperature. The minima of potential energy $W_P(s)$ had a periodicity of 0.15-0.3 nm.

A large number of other adhesive effects were observed by modeling methods: the formation of adhesive avalanches, plastic flow of the probe material with the formation of crow ions and the generation of dislocations, the vibrational mechanism of compression and destruction of metal nanoparticles during an inelastic impact. Of course, there are certain contradictions between experimental studies and the results of molecular dynamics modeling: experimental studies, unlike molecular dynamics calculations, do not always reveal hysteresis of adhesive forces.

Nanotribological substantiation of the effects of "sticking-sliding" from the point of view of adhesion indicates that it is possible to create conditions for the functioning of couplings of parts of machines and mechanisms when frictional forces are minimal [23,24] . This condition determines the maximum wear resistance, and therefore reliability, and the maximum efficiency of the functioning of machines and mechanisms.

Conclusions

1. It has been found that the study of nanotribological processes in the materials of the samples and parts of machines and mechanisms should be carried out by the methods of the surface force apparatus, scanning tunneling microscopy, and interpreted by the methods of molecular dynamics and classical contact mechanics.

2. During the consideration of theoretical models of the tribon level, much attention is paid to "dry" adhesive and non-contact dynamic friction. At the same time, the effects of "ploughing" and "wet" friction, thermodynamic aspects of nanotribology are taken into account, physical processes in tribocontacts are discussed: "sticking-sliding", damping of motion of adsorbed films, adhesive, chemical and others. The evolution of the structure of nanocontacts is analyzed by the method of molecular dynamics.

3. At the atomic level, the nanotribocontact effect of the conjugated surfaces of the "sticking-sliding" parts samples was considered, with the measurement and analysis of the magnitude of the lateral and normal forces acting on the probe. Various combinations of probe materials and samples of parts were subject to investigation. The "sticking-sliding" effect was detected by the surface forces apparatus, which is characteristic of the translational symmetry of the material of the parts samples.

4. An attempt was made to explain the "sticking-sliding" effect based on the modernized classical ideas of Tomlinson and the method of molecular dynamics. The probe was considered as a set of point particles of concentrated mass, taking into account the multiatomic structure of the material. The contact and movement of the probe with the surface of the sample was considered in the "probe-surface" system with minimal potential energy and under conditions of lateral loading. When exiting the potential well, this system relaxes and excess energy quickly dissipates from the contact region through the electron-phonon subsystem. Both hard and soft contact of the atomic force microscopy cantilever with the surface of the part sample was considered.

5. Differences between conservative and dissipative forces acting on the probe whose movement corresponds to the friction loop are taken into account. It was found that after a sharp decrease in the initial phase of the reverse movement of the probe, the lateral force is close to zero and the "probe-sample surface" contact is unloaded. Sharp changes in the lateral force are irreversible and are associated with the dissipative nature of the sliding process.

6. It is shown that the atomic periodicity of the "sticking-sliding" effect can be explained by the model of the formation and breaking of adhesive bonds. Old adhesive bonds behind the contact spot are broken, reducing the resistance to the translational movement of the probe, and new ones arising in front of the contact spot capture

it forward. This can be described by the model of "atoms-magnets", the system of which moves with a constant horizontal speed and visualizes the atomic effect of "sticking-sliding" at the macro level.

7. Adhesion effects play a significant role in nanotribology, as they determine the contact area and the interaction of the samples with each other and with the probe in the mode of "input-withdrawal" of the probe and measurement of "friction force-load force" dependencies. It is shown that the parameters: shear stress and specific work of adhesion can be used to substantiate the regularities of the "sticking-sliding" processes. The first parameter is proportional to the critical lateral force, and the second is equal to the specific energy relative to a unit of contact area. The work of adhesion is considered both for "dry" and "wet" friction. The Johnson-Kendel-Roberts theory and the Deryagin-Mullier-Toporov theory were used to explain the elastic adhesive contacts for the residual friction force and the probe separation force.

8. It is shown that there is a connection between the processes of friction and adhesion, which is due to the internal molecular structure and frictional hysteresis is observed. The correlation between the macroscopic values of the surface energy of materials and their shear modulus for homogeneous contacts, as well as between the tangential stress and the specific work of adhesion was determined. The substantiation of adhesive effects and the effect of "sticking-sliding" testify to the possibility of controlling the force of friction and creating conditions when the force of friction is practically absent. This state is characterized by maximum wear resistance, and therefore high reliability and maximum efficiency of tribocouplings of parts of machines and mechanisms.

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Аулін В.В., Тихий А.А., Кузик О.В., Лисенко С.В., Гриньків А.В., Жилова І.В., Лівіцький О.М.
Обґрунтування впливу закономірностей протікання нанотрибологічних процесів в матеріалах спряжень деталей на підвищення зносостійкості, надійності та ефективності функціонування машин і механізмів

В статті з'ясовано сутність нанотрибологічних процесів в матеріалах спряжень зразків деталей методами апарату поверхневих сил, скануючої тунельної та атомносилової мікроскопії. Обґрунтування механізмів їх протікання дано методами молекулярної динаміки та класичної контактної механіки. Увагу надано сухому адгезійному і безконтактному динамічному тертю спряжених зразків, фізичним процесам в трибоконтактах "прилипання-ковзання", адгезійні ефекти та ін. Проаналізовані величини діючих на зонд латеральних та нормальних сил. Зонд розглядали як сукупність точкових частинок зосередженої маси з мультиатомною структурою матеріалу. Контакт і рух зонду з поверхнею зразка розглядали в системі "зонд-поверхня" з мінімальною потенціальною енергією та латерального навантаження і врахуванням консервативних і дисипативних сил.

Ефект "прилипання-ковзання" обґрунтовано за допомогою апарату поверхневих сил. Атомарну періодичність ефекту пояснено на основі моделі утворення і розриву адгезійних зв'язків та моделі "атоми-магніти". Показано, що закономірності протікання процесів "прилипання-ковзання" можливо з'ясувати використавши параметри напруження зсуву і питому роботу адгезії.

Для пояснення пружних адгезійних контактів доцільно використати теорію Джонсона-Кендала-Робертса, а для залишкової сили тертя і сили відриву зонду – теорію Дерягіна-Муллєра-Топорова.

Показано, що існує істотний зв'язок процесів тертя і адгезії. Визначено кореляційну залежність між макроскопічним значенням поверхневої енергії матеріалів і їх модулем зсуву для однорідних контактів.

На основі адгезійних ефектів та ефекту "прилипання-ковзання" можна управляти силами тертя і створювати сприятливі умови їх відсутності, що дає підстави отримати високу зносостійкість трибоспряжень деталей, їх надійність та максимальну ефективність функціонування машин і механізмів.

Ключьові слова: адгезійні ефекти, прилипання-ковзання, спряжені поверхні, латеральні сили, тертя, зносостійкість, надійність, ефективність.

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Research of the vacuum thermocyclic nitrogen process in a plasma pulsing glow discharge

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Abstract

As a result of the studies, the regularities of the influence of vacuum thermocyclic nitriding in a pulsating glow discharge plasma parameters on the microhardness, the diffusion saturation depth, the magnitude and distribution of residual stresses in the hardened layers of steel surfaces are established. Based on the use of expert assessment methods and the results of a series of screening experiments, optimization criteria (endurance limit and corrosion resistance) and controlled factors for mathematical modeling of the formation of strengthened ion-nitrated surface layers are determined. A mathematical model of the technology of the formation of reinforced surfaces of the vacuum thermocyclic nitriding in a pulsating glow discharge plasma according to the criteria of endurance and corrosion resistance is obtained. An analysis of the studies showed that there are no general conclusions and recommendations on the selection of optimal technological parameters of the vacuum thermocyclic nitriding in a pulsating glow discharge plasma that would be used for the practical application of this technology. These circumstances confirm the need for further study of the vacuum thermocyclic nitriding in a plasma of a pulsating glow discharge of vacuum thermocyclic nitriding in a pulsating glow discharge plasma technology and the feasibility of its optimization.

Key words: vacuum thermocyclic nitriding, mathematical model, technological process, plasma, pulsating glow discharge

Relevance of the research topic

Analysis of literary sources and recent research, as well as patent information search showed that the wide use of vacuum thermocyclic nitriding technology in pulsating glow discharge plasma is limited by the lack of research on the interrelationship of factors that determine the course of the process of vacuum thermocyclic nitriding in pulsating glow discharge plasma and generalizing conclusions and recommendations for choosing technological parameters of this technology. These circumstances confirm the relevance and necessity of studying the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge.

Formulation of the problem

Most of the reasons for the destruction of structural elements of parts of machines and mechanisms are related to their cyclic strength, namely thermomechanical fatigue, which is expressed in the gradual accumulation of damage in the material under conditions of simultaneous exposure to variable loads, aggressive environment and temperature. This leads to the appearance of a fatigue crack, its development and the final destruction of the material. One of the important and promising directions in solving problems related to increasing the resistance to thermomechanical fatigue of structural elements is the use of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge. In order to effectively analyze the mechanism of phenomena and control the technological process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge, it is necessary to identify the interrelationship of the factors that determine the course of the process.

Analysis of recent research and publications

Based on the theory of thermocyclic fatigue and the phenomenon of anomalous mass transfer during impulse impact at the Institut problem micnosti imeni G.S. Pisarenka of the National Academy of Sciences of Ukraine developed the technology of accelerated nitriding in a glow discharge with a cyclic temperature change due to the periodic supply of discharge voltage. The technology of ion-plasma thermocyclic nitriding is protected by patents of Ukraine and has no analogues in domestic and international practice [1-4].

With the help of the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge, it is possible to process various parts. For example, crankshafts, sleeves of internal combustion engines, gears of various modules, screws of extruders, shafts, stamps, molds, long parts with holes, etc. Ion nitriding is used for processing cast iron and various steels and alloys: structural and tool, martensitic aging, corrosion-resistant, chromium and chromium-nickel steels of the ferritic and austenitic class, etc. A promising new technology for strengthening titanium, refractory metals - niobium, molybdenum.

The new technology is synthesized on the basis of three theories, phenomena and effects: theory of thermal fatigue; discrete-pulse input of energy in heat technologies; of the effect of anomalous mass transfer under the action of impulse deformations. The effect of anomalous mass transfer is provided by thermal stresses arising due to cyclical changes in process temperature. The theory of thermal fatigue determines the conditions for obtaining values of thermal stresses sufficient to accelerate the diffusion of nitrogen into the metal, but safe so as not to damage the product. The discrete-pulse input of energy provides an increase in the heating rate by 2...5 times, which allows to increase the thermal stress and, accordingly, the rate of nitrogen diffusion [1-4].

The technology of accelerated nitriding in a glow discharge with a cyclical change in temperature due to the periodic supply of discharge voltage is based on the "three whales" - an effective solution to a complex of interrelated scientific and methodological problems on the border of thermomechanics, metallophysics and thermophysics [1-4]. The technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge should be considered as an alternative to classical cementation followed by quenching. It should be emphasized that the American standard ASTM A 706 limits and prohibits quenching and finishing machining due to technical difficulties and increased cost. The new technology does not require finishing mechanical processing [1, 2, 4].

The main feature of the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge is the use of the effect of anomalous mass transfer of nitrogen in the surface of the processed part by creating a field of thermal stresses in the surface layer due to the cyclic inclusion and exclusion of the glow discharge. Taking into account the acceleration of mass transfer during thermal cycling due to the occurrence of thermal stresses, it was decided to develop a chemical-thermal treatment technology based on the classical ion nitriding technology, which works in isothermal mode all over the world. The technology of ionic nitriding is attractive for improvement because the global trend is to reduce the duration of chemical-thermal treatment, which is one of the most energy-intensive in mechanical engineering. Previous attempts to create a technology of thermocyclic ion nitriding gave positive results. [1-4]:

The technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge does not use furnace devices. Compared to furnace nitriding, ion nitriding has the following advantages [1-4]: it accelerates diffusion processes by 0.5-2 times; allows obtaining a diffusion layer of adjustable composition and structure; characterized by slight deformations of products and a high class of surface cleanliness; makes it possible to nitride corrosion-resistant, heat-resistant and martensitic-aging steels without additional processing; significantly reduces the total time of the process by reducing the time of heating and cooling the cage; has high efficiency, increases the coefficient of electricity use, reduces the consumption of saturating gases; non-toxic and meets the requirements for environmental protection.

Ammonia is used in the world practice of nitriding. The ecological advantage of the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge consists in the rejection of the use of ammonia. Processing is carried out by a glow discharge in a mixture of argon and nitrogen. This also eliminates the negative effect of hydrogen on the core of the part - hydrogen embrittlement and hydrogen corrosion. The replacement of classical gas nitriding in an ammonia environment with the technology of vacuum thermocyclic nitriding in plasma of a pulsating glow discharge in a mixture of nitrogen and argon provides a 10-fold reduction in the duration of processing [1-4]. Unlike chemical-thermal treatment, the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge does not create continuous heating of the part, but provides heating of only the surface layer to the depth necessary for its strengthening. Heating occurs due to the energy of the glow discharge, so there is no need to use furnaces [1-4].

The difference between the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge and the classic technologies of chemical-thermal treatment, which use isothermal mode: the process of chemical-thermal treatment is accelerated by 2...6 times; due to the absence of furnace devices and thorough heating of the part, as well as due to pauses in the power supply during the half-cycle of part cooling, the cyclic nature of the high-speed discrete energy input, the acceleration of diffusion processes, the processing time is reduced by 2-3 times, electricity costs are reduced, and the energy consumption of the technology is reduced by 10 times [1-4].

Thus, the cyclic nature of the heating of the product makes it possible to reduce the required power of electrical power sources by 2-5 times, which refers the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge to the energy-saving category. The technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge increases the hardness of the surface by 20%, does not change the shape and dimensions of the part, as well as the roughness of the surface. Therefore, it is used as a finish, without final mechanical processing. This greatly simplifies the technological process of production while increasing the durability and wear resistance of the part by 4 times, the limits of multi-cycle fatigue by 25% [1-4].

One of the important and promising directions in solving problems related to increasing the resistance to thermomechanical fatigue of structural elements is the use of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge. However, the wide use of the technology of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge is limited by the lack of determination of the relationship of the factors that determine the course of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge and the lack of recommendations for the selection of technological parameters of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge. These circumstances confirm the need for further study of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge.

The purpose of the article is to provide an analysis of the phenomena in the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge and to determine the interrelationship of the factors that determine the course of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge.

Presenting main material

The process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge is implemented in two stages: cleaning the surface of the ped by nitriding and nitriding itself. The technological process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge is reduced to the following operations [1-4]:

- degreasing of parts;
- installation of parts on the device, which at the same time should serve for local protection against nitriding (cover the protective surface with a metal and dielectric screen). The gap between the part and the screen is allowed no more than 0.3-0.5 mm;
- installation of parts, thermocouples and a witness to monitor nitriding results in the furnace chamber;
- cleaning the surface of the part by cathodic spraying for 15…40 minutes under a voltage of 800…1000 V at a pressure of about 133 Pa. Cathodic sputtering of the treated surface ensures heating of parts up to 300…400°C;
- reaching the specified nitriding temperature and exposure to obtain the desired thickness of the nitriding layer (tables 1, 2). The pressure during nitrogen saturation is maintained in the range of 400…650 Pa, and the operating voltage is 350…550 V;
- cooling of parts in the furnace chamber to 150…200°C at a pressure of 13.0…65 Pa. lasts 1.0…2.0 hours.

Table 1

The main parameters of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge of parts made of different steels

Steel brand	Temperature, °C,	Gas mode	Duration in hours to obtain a layer thickness, mm					Hardness on the surface, HV
			0,15-0,2	0,2-0,25	0,25-0,3	0,3-0,35	0,35-0,4	
40Kh	520	1,2	4-5	7-9	9-12	12-15	15-18	500-550
40KhFA	520 520	1 2	4-5 4-5	6-8 6-8	9-12 8-10	15-18 12-15	- 15-18	- 510-560
18KhGT	530 550	1,2 1,2	4-5 3-4	6-8 4-5	9-12 6-8	15-18 9-12	- 15-18	620-680 530-600
30Kh3MF	530 530	1 2	4-5 4-5	6-8 5-7	9-12 6-8	15-18 9-12	- 15-18	700-760 -
38Kh2MYuA	550	1,2	4-5	5-7	7-9	9-12	15-18	900-950

Samples made of 40Kh13 steel with a size of 30x30 mm and a thickness of 10 mm were used in the experimental studies. The gas mode of nitriding (Table 2) provides uniform hardening of the surfaces of the samples (uniform thickness of the diffusion layer). Technological parameters of the formation of reinforced layers: temperature of thermocycling - 550 ± 30˚C; pressure – 25 … 150 Pa; processing time - 10 hours; the ratio of reaction gases is 80% Ar + 20% N_2.. With the help of the proposed technology, it is possible to process various parts. For example, crankshafts, sleeves of internal combustion engines, gears of various modules, screws of extruders, shafts, stamps, molds, long parts with holes, etc. Ion nitriding is used for processing cast iron and various steels and alloys: structural and tool, martensitic aging, corrosion-resistant, chromium and chromium-nickel steels of the ferritic and austenitic class, etc. A promising new technology for strengthening titanium, refractory metals - niobium, molybdenum.

Analysis of literary sources and recent research, as well as patent information search [1-4] shows that the wide use of vacuum thermocyclic nitriding technology in the plasma of a pulsating glow discharge is limited by the lack of research on the relationship of factors that determine the course of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge discharge and generalizing conclusions and recommendations on the selection of technological parameters of this technology. These circumstances confirm the relevance and necessity of studying the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge.

A significant number of technological parameters of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge in combination with a wide range of materials from which the strengthened surface layer is formed give technologists a wide range of alternative options. In such a situation, the effectiveness of the decisions taken will depend on the availability of the necessary criteria for assessing the performance of the structural material under the specified operating conditions. For the successful development of a technological process, the strengthened surface layer must have a physical meaning and sufficiently characterize the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge [1-5].

Table 2

The main technological parameters of the nitriding process of parts made of various steels

Mode No processing	Diffusion saturation time, min.	Reaction gas pressure, Pa	The composition of the reaction gas	Gas temperature, °K	Operating temperature, °K	Surface microhardness layer, MPa	Diffusion thickness layer, μm
1	180	125	90%N_2 + 5%C_3H_8 + 5%Ar	773	788	3700	288
2	150	200	95%N_2+ 5%C_3H_8	873	725,5	10062	125
3	210	75	80%N_2 + 5%C_3H_8 + 15%Ar	673	850,5	9955	286
4	150	175	80%N_2 + 5%C_3H_8 + 15%Ar	873	819,2	8175	215
5	210	50	90%N, + 5%C,H_8 + 5%Ar	773	694,3	10590	142
6	180	100	90%N_2 + 5%C_3H_8 + 5%Ar	673	881,8	8270	253
7	240	225	95%N_2- 5%C_3H_8	773	756,8	8985	208
8	90	250	80%N_2 + 5%C_3H_8 + 15%Ar	673	709,9	9100	267
9	180	125	95%N_2+ 5%C,H_8	873	834,9	8945	181
10	150	50	80%N_2 + 5%C_3H_8 + 15% Ar	773	772,4	10235	179
11	210	175	90%N_2 + 5%C_3H_8 + 5% Ar	673	897,3	8144	312
12	150	100	95%N_2+ 5%C_3H_8	873	803,6	8335	228
13	210	225	80%N_2 + 5%C_3H_8 + 15% Ar	673	678,6	10835	267
14	180	150	95%N_2+ 5%C_3H_8	773	866	8841	215
15	240	25	90%N_2 + 5%C_3H_8 + 5% Ar	873	741	9150	191
16	90	150	90% N_2 + 5%C_3H_8 + 5% Ar	673	780	8659	212

When strengthening the surfaces of structural elements, the term structural or structural strength of metals is widely used [6-8]. The concept of structural strength includes a number of parameters or indicators that characterize not only the strength of structural elements, but also their durability (resource), bearing capacity, and most importantly, reliability. The indicators of structural strength of elements include strength under various types of load at low and high temperatures, under the influence of the surrounding environment (corrosive-erosive, etc.) [6-8]. By using the technological process of the reinforced surface layer, which affects the quality of the surface layer, it is possible to control the values of the parameters of the structural strength of the materials. Evaluating the operating conditions of the most heavily loaded structural elements, the simultaneous influence of dynamic loads, elevated temperatures, and a corrosive environment was established. Among dynamic loads, cyclic loads are of particular interest. With systematic repetition of loading and unloading, defects in the material structure accumulate, which leads to the appearance of microscopic cracks, the combination of which causes fatigue failure. It is possible to establish the maximum cyclic load at which the material does not collapse with the help of thermomechanical high-frequency fatigue tests, namely, if it is necessary to determine the value of the endurance limit of the strengthened structural material. Corrosion damage significantly reduces the mechanical properties of the structural material. Thus, it is advisable to study the endurance limit and corrosion resistance, which is characterized by a specific increase in mass, as a surface with a strengthened surface layer.

To study the hardening process, the parameters that most affect the endurance limit and corrosion resistance of hardened surface layers were determined: time of diffusion saturation, pressure and composition of the reaction gas, temperature of the diffusion saturation process, and operating temperature (Table 3). It should be noted that the values of such parameters as the pressure and temperature of the reaction gas given in the table during the process of the strengthened surface layer are not constant: the pressure of the reaction gas changes periodically (with a period of 15...30 min.), and the temperature fluctuates in within 25...35°C.

Table 3

Nitriding process parameters affecting the quality of parts surfaces

№	Parameters	Value
1	Diffusion saturation time, min.	90...240 (крок 30)
2	Reaction gas pressure, Pa	25...250 (крок 25)
3	Gas temperature, °K	673...873 (крок 100)
4	The composition of the reaction gas	1) 90%N_2 + 5%C_3H_8 + 5% Ar; 2) 95%N_2+ 5%C_3H_8; 3) 80%N_2 + 5%C_3H_8 + 15% Ar
5	Operating temperature, °K	663...913

Studies of the microhardness of the surface layers after the strengthened surface layer revealed an increase in its values to 11250 MPa (Table 4.) and a gradual decrease to 4200 MPa at a depth of up to 310 microns.

Table 4

Microhardness of the surface layers of the sample after nitriding

Mode No processing	Microhardness of the surface layer, MPa	
	without pulsating glow discharge	with a pulsating glow discharge
0	3100	3700
1	9032	10062
2	8164	9955
3	7414	8175
4	8614	10590
5	8047	8270
6	8089	8985
7	8154	9100
8	7534	8945
9	9111	10235
10	9904	8144
11	7040	8335
12	9898	10835
13	7950	8841
14	8061	9150
15	7769	8659
16	7179	8663

Processing modes are presented in Tables 2 and 3. From the analysis of the results given in Table 4, it is clear that nitriding in a pulsating glow discharge contributes to an increase in the microhardness and depth of hardening of the treated surface layers. In any case, such values of the microhardness of the samples are 2.5...3.0 times higher than those without the influence of a pulsating glow discharge and 1.5 times higher than those of the samples after gas nitriding (90%N2+10%Ar; T=600°C; 1=4.0 h).

The analysis of the data in Table 4 allows us to conclude that there are some ranges of nitriding temperature and reaction gas pressure, at which the microhardness of the surface layers reaches its maximum values: for nitriding temperature, this range is within 550...600 °C, for gas pressure - in between 200...230 Pa. As the time of diffusion saturation increases, the microhardness of the surface layer decreases, and more intensively - after 2 hours of treatment. With regard to the effect on the microhardness of the composition of the reaction gas, it was established that it acquires maximum values when using a mixture of 90%N_2+ 5%C_3H_8 + 5%Ar, and minimum values - when using a mixture of 80%N_2 + 5%C_3H_8 + 15%Ar.

As a result of conducting research on the anti-corrosion ability of ion-nitrogenized steel samples, an increase in corrosion resistance by 1.7...3.1 times was found (Table 5). This is of particular interest when the benefits of nitriding are also aimed at increasing fatigue strength. Processing modes of the reinforced surface layer for the data of Table 5 are presented in Table 2.

To determine the fatigue resistance, at least 10-15 samples strengthened by vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge were studied. Each sample was brought to failure, while the amplitude of oscillation of the sample and the frequency of loading were kept constant during the entire time of the study almost until its failure. Fatigue test base N=107 load cycles. During the fatigue test at elevated temperatures, the sample was heated to the specified temperature before loading and kept in the heating chamber for an additional 30 min. The moment of the beginning of the destruction of the sample was determined by the drop in the resonance frequency of its oscillations by 10...15 Hz. The quantitative characteristics of fatigue are influenced by the temperature of the surrounding environment. As the test temperature increases, starting from 500 °C, the endurance limit decreases.

Table 5

Results of corrosion resistance research of nitrided samples

Mode No processing	Specific mass increase of sample A, after 10 hours of testing	
	without pulsating glow discharge	with a pulsating glow discharge
0	0,58	0,40
1	0,17	0,12
2	0,22	0,18
3	0,19	0,17
4	0,17	0,15
5	0,20	0,18
6	0,20	0,19
7	0,21	0,18
8	0,19	0,16
9	0,16	0,14
10	0,18	0,18
11	0,21	0,20
12	0,16	0,14
13	0,19	0,16
14	0,18	0,15
15	0,20	0,20
16	0,21	0,18

Diffusion processes on the surface of the sample are activated under the non-additive influence of temperature and the external environment, which leads to the appearance of microscopic surface cracks, which are the beginning of fatigue failure. Fatigue resistance is influenced by both the number of load cycles and the time the sample is exposed to high temperatures under conditions of cyclic loading. Vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge limits the speed of diffusion processes, which has a significant effect on increasing the endurance limit. Thanks to the technological process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge, it was possible to increase the endurance limit of samples by 15...20% with an increase in the number of cycles to destruction in the languages of simultaneous action of cyclic loads and temperature.

On the basis of the conducted experimental studies, it was established that the main mechanisms of increasing the endurance limit of materials due to the application of the technological process of diffusion saturation of the surface with nitrogen in a pulsating glow discharge in the thermocyclic mode are: strengthening of surface layers; creation of a favorable scheme of residual stresses; change in patterns of deformation of surface layers; change in chemical and adhesive properties of the surface. The relatively small depth of penetration of nitrogen ions cannot be considered as a factor limiting the possibilities of this type of treatment to increase the endurance limit, because the implementation of treatment modes is related to the modification of submicron-thick surface layers. In addition, it was experimentally established that layers whose thickness is several times greater than the ion-nitrogenized region can have an increased endurance limit.

The strengthening of the surface layers occurs according to the following mechanisms, the contribution of which depends on various factors (temperature and grade of the material being processed, parameters of the technological process, etc.): the formation of structures with strengthening phases (nitrides, carbonitrides, etc.), which cause dispersion hardening; deformation hardening during plastic change of the shape of the ion-nitrogen layer; strengthening due to the formation of solid solutions, which create an energy barrier and make it difficult to move dislocations; decrease in grain size, which leads to an increase in the area of grain boundaries and hinders the movement of dislocations.

As you know, the greatest danger from the point of view of ensuring a high level of the endurance limit of materials is represented by residual tensile stresses. They contribute to the development of near-surface cracks, the penetration of molecules of the external environment into the origins of microcracks and accelerate the diffusion of impurity atoms. In the conditions of multi-cycle fatigue, the residual compressive stresses that occur during the diffusion of nitrogen into the surface layers acquire great importance. In the case of diffuse saturation of the surface with nitrogen in a glow discharge, a nitrogen atom embedded in the matrix pushes neighboring atoms apart, creating residual compressive stresses. These stresses effectively protect the surface from destruction.

Ionic nitriding treatment significantly affects the chemical and adhesive properties of the surface of hardened materials. The formation of chemical compounds in steels and alloys due to the introduction of nitrogen or an increase in its concentration limit changes the speed of chemical reactions and the kinetics of the growth of oxide films, increases their adhesion to the base. This leads to a decrease in the intensity of the formation of adhesion knots and contributes to the improvement of the mechanical properties of materials.

Conclusions

The analysis of literary sources and recent studies showed that the wide use of the technology of vacuum thermocyclic nitriding in plasma of a pulsating glow discharge is limited by the lack of research on the relationship of factors that determine the course of the process of vacuum thermocyclic nitriding in a plasma of a pulsating glow discharge and general conclusions and recommendations for the selection of technological parameters of this technologies.

Based on studies of the influence of the stress state and mechanical properties on the strength characteristics, a mechanism for increasing the endurance limit of ion-nitrogenized surface layers has been established. On the basis of the analysis of the stress-strain state, it is possible to predict the characteristics of cyclic strength, which allows controlling the regimes of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge within wide limits.

As a result of the conducted research, the regularities of the influence of the parameters of the technological process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge on microhardness, the depth of diffusion saturation, the magnitude and distribution of residual stresses in the strengthened layers of steel surfaces have been established. It is shown that:

- to obtain the maximum microhardness of the surface layer, which reaches 7600 MPa, the reaction gas pressure must be within 200...250 Pa, the diffusion saturation time - 90...150 min.; process temperature -- 500...600°C;

- to obtain the maximum thickness of the diffusion layer of 150...305 μm, the pressure of the reaction gas must be within 200...250 Pa, the diffusion saturation time - 180...240 min.; process temperature - 550.. .600°C;

- residual compressive stresses of the order of 445...950 MPa occur in the ion-nitrogenized layers, the level and distribution of which depend on the technological parameters of the process of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge and on the preliminary heat treatment.

As a result of conducting research on the properties of the surface layers of samples strengthened by nitriding, it was established that, thanks to the use of vacuum thermocyclic nitriding in the plasma of a pulsating glow discharge, the corrosion resistance increases by 3.1 times, and the endurance limit of steel structures at temperatures up to 640°C increases by 15...20%.

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Рутковський А.В., Радько О.В., Солових Є.К., Катеринич С.Є., Солових А.Є. Дослідження процесу вакуумного термоциклічного азотування у плазмі пульсуючоготліючого розряду.

Одним із важливих та перспективних напрямків у вирішенні задач щодо підвищення опору термомеханічній втомі елементів конструкцій є використання вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду. Широке використання технології вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду обмежено відсутністю визначення взаємозв'язку факторів, що визначають хід процесу вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду та відсутністю рекомендацій по вибору оптимальних технологічних параметрів процесу, Ці обставини підтверджують необхідність подальшого вивчення процесу вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду.

У результаті проведених досліджень встановлено закономірності впливу параметрів вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду на мікротвердість, глибину дифузійного насичення, величину та розподіл залишкових напружень у зміцнених шарах сталевих поверхонь. На підставі використання результатів експериментів визначено межу витривалості і корозійну стійкість зміцнених іонно азотованих поверхневих шарів. У результаті проведення досліджень властивостей поверхневих шарів зразків, зміцнених азотуванням, встановлено: що завдяки використанню вакуумного термоциклічного азотування у плазмі пульсуючого тліючого розряду, товщина дифузійного шару складає 40…300 мкм; мікротвердість поверхневого шару досягає 7600 МПа; виникають залишкові напруження стиску порядку 445…950 МПа, корозійна стійкість підвищується у 3,1 рази, а. межа витривалості сталевих конструкцій при температурах до 640 °С підвищується на 15...20%.

Ключові слова: вакуумне термоциклічне азотування, математична модель, технологічний процес, плазма, пульсуючий тліючий розряд