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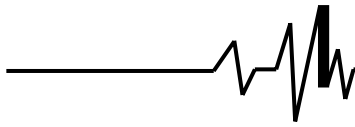
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**Вінницький національний
аграрний університет****УДК 621.3.035.183****DOI: 10.37128/2306-8744-2022-2-7****CREATING SURFACE LAYERS OF
PARTS WITH INCREASED
TRIBOLOGICAL
CHARACTERISTICS USING COLD
GAS-DYNAMIC SPRAYING**

One of the transitions to the path of intensification of the production processes is the perceptibly low stability of the details of the nodes in the possession of these production processes. The stamina of the details is small, vindictive, nasampered, rubbing in pairs, especially quiet, which works out of significant tensions in aggressive middles. The wear of the upper balls of parts can ruin the possession, which leads to the waste of energy and material resources. One of the ways to solve the problem is the creation of functional coatings on the surfaces that are resistant to aggressive environments. The results of the analysis of antifriction properties of materials containing copper, tin, lead, aluminum, and polymers are presented. The advantages and disadvantages of antifriction properties of the materials in question are shown and the possibility of their application on the surface of parts using cold gas dynamic spraying. The use of liquid and solid antifriction materials as lubricants is analyzed. Attention is paid to materials with a crystalline structure similar to the structure of graphite, known as 2D structures (two-dimensional materials)." The most studied 2D materials are MoS₂ and carbon-based compounds, including graphene and graphite. The diagram of the interaction of sliding surfaces, including molecular deformation, wear, bonding, the thermal effect, and environmental influence is shown. It is noted that the application of antifriction materials to the surface of parts can be carried out using cold gas-dynamic spraying. Found that compared to the material of the substrate AA7075, the coefficient of friction of sliding of the spray coating with the crystal of copper-graphite powder was reduced by 47% - 62%. Rubber composite coatings are made of a mechanical mixture of aluminum powder A30-01 and copper C01-00. The dependence of the coefficients of spraying aluminum and copper on the content of aluminum in the composite mixture that is sprayed is obtained. until it reaches 61%. At higher concentrations of aluminum (more than 66%) the coefficients of spraying aluminum, copper, and their mixtures coincide.

Keywords: antifriction materials, cold gas-dynamic spraying, antifriction coatings.

Introduction. One of the obstacles to the intensification of production processes is the relatively low stability of the components of the equipment of these production processes. Low stability of details arises, first of all, in friction pairs, especially those working with considerable loading in aggressive environments. Wear of the upper layers of parts can destroy equipment and lead to loss of energy and material resources. One of the ways to solve this problem is to create on the friction surfaces

of functional coatings resistant to aggressive environments. Such coatings must have anti-friction properties, namely to provide low friction losses, low slip coefficient and low wear rate of the surfaces of parts. The coating material in specific operating conditions must be resistant to oxidation at certain temperatures, to be resistant to corrosion in aggressive environments. Anti-friction coating materials must work in a wide range of friction speeds, loads, temperatures, and have high wear



resistance. To ensure the wear-resistant properties of the friction zone of machine parts, antifriction coatings must have the following properties: high thermal conductivity; effective lubrication with lubricants; ability to create protective films on the surface; have satisfactory workability, ie the ability of the material during friction to increase the area of actual contact, which reduces the specific pressure and temperature on the friction surfaces.

According to statistics, about 20% of world energy production is spent on overcoming friction [1]. Significant economic losses due to friction have become an incentive to combine the three important areas of research, friction, lubrication and wear under a common research method [2]. Therefore, the term tribology was introduced in 1960 to connect these three important interdisciplinary fields of research.

Analysis of recent research. Let's analyze antifriction materials that can be applied to the surface by cold gas-dynamic spraying.

Tin and lead materials called babbitts have hardness (HB 12 ... 32) and melting point (240 ... 320 °C), and excellent workability. They are superior to all other alloys in antifriction properties, but inferior in resistance to fatigue. Babbitts are used only for a thin (less than 1 mm) coating of the sliding work surface. The most famous babbitts based on tin are the following brands B93, B88, B83, B83C. All of them have a structure in the form of a heterogeneous mechanical mixture of solid solutions based on tin and based on the intermetallic compound SnSb. These alloys have high wear resistance due to the high strength of secondary structures that form on the surface of the babbitt. Babbitt can be used to cover the working surface of parts by cold gas-dynamic spraying.

Copper-based antifriction materials are currently the most widespread, primarily bronze, which is an alloy of copper with other non-magnetic metals. Bronzes can be tin, aluminum, etc. Bronze is also used as a basis for powder antifriction materials and porous coatings. The most common antifriction coating in the form of porous bronze impregnated with oil, as well as powdered bronze graphite materials. Bronze, which contains 9 ... 11% tin, has the best antifriction properties. Porous bronze-based anti-friction coatings are used to make plain bearings that operate in unloaded assemblies, such as devices with low sliding speeds (less than 1,5 m / s) and low specific loads (approximately 0,5 ... 1 MPa). Such bearings do not require lubrication for 3000 ... 5000 h, have a low coefficient of friction (0,01 ... 0,04), low noise and are able to operate in the temperature range from -60 to +120 °C. How to apply additional lubrication the maximum load for porous bronze will reach 8 MPa.

Materials obtained by powder metallurgy containing copper have high antifriction characteristics. These include bronze graphites, hard-alloyed bronzes, copper graphites.

Graphite does not interact with copper or tin, it is used as a mechanical impurity, as a solid oil, in the amount of 1 to 25% by volume, depending on the working conditions of the materials. Graphite in the process of friction gradually forms a graphite film on the contact surface of friction pairs. The film is constantly restored in case of mechanical damage in some parts of the friction surface. These materials include bronzes with traffic content BrOGr10-3, BrOGr9-3, BrOGr8-4. The properties of sintered bronzes and bronze graphites can be significantly improved by alloying elements such as titanium, nickel, lead, zinc, cobalt, iron, aluminum and others with a porosity of up to 12%. Their tensile strength reaches 3,5 MPa.

Copper graphite materials in electrical engineering are used for the manufacture of fixed contact, radial seals and brushes. Their composition is determined according to the required properties. In these electrical parts, graphite increases wear resistance and contact resistance, and copper provides electrical conductivity. Graphite content can range from a few percent to 75%. Tin, lead and zinc are added to improve the properties of brush materials. Lead improves hardness. Tin and zinc strengthen the material, and lead acts as a lubricant. The wear resistance of copper-graphite materials obtained by powder metallurgy in the conditions of brush operation is much higher, compared with conventional brush materials.

Our experiments have shown that antifriction materials based on copper are quite well applied to the surface of parts by cold gas-dynamic spraying.

Aluminum alloys as antifriction materials have corrosion resistance in lubricants, sufficient fatigue strength, relatively high burr resistance and high antifriction properties. Aluminum alloys are used in both monometallic and bimetallic versions. Aluminum antifriction alloys are made by powder metallurgy, have significant advantages such as low specific weight, low cost and significant corrosion resistance. These alloys are well suited for their application on the surface of parts by cold gas-dynamic spraying.

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The purpose of the research is to analyze antifriction materials and create antifriction layers on friction surfaces by cold gas-dynamic spraying.

Presentation of the main material.

Liquid antifriction materials are used in most industries, such as mechanical engineering and agro-industrial complex. They contain a base polymer with the addition of various additives. Additives are strongly influenced by the operating conditions of the friction unit, such as load, speed and temperature; also the essential factors of efficiency are viscosity of oil and a design of lubricating system. The lubrication system must provide an adequate pressure drop to ensure the inflow of liquid polymers to the required parts depending on the viscosity. The narrow range of effective operating spectrum and the complexity of designing the pressure drop for the lubricant flow complicates the use of liquid lubricants in extreme operating conditions, when temperature and pressure change significantly or there are gases and radiation that may react with lubricant, deteriorating its lubricant properties [3].

Solid antifriction materials have been developed primarily for installations where liquid antifriction materials are not effective, for example, in areas of high temperatures, high and ultra-low pressures, which are characterized by extreme conditions [4]. Under these conditions, liquid lubricants are inadequate both in terms of maintaining antifriction properties and in terms of design limitations.

Graphite was one of the first materials to be used as a solid lubricant or as an additive to liquid lubricants, which later led to the study of graphite-like materials with a crystalline structure known as two-dimensional (2D) materials. These antifriction materials are used to reduce friction between metal surfaces because they provide a low slip coefficient between surfaces. Materials such as MoS₂, h-BN and boric acid, along with graphite, are among the solid lubricants used in industry [5-6]. The layered structure of these materials is responsible for the lubricating properties in the friction zone, and each layer of MoS₂, h-BN and boric acid is covalently linked to each other by sp₂ or sp₃ hybridization, which leads to stronger bonds [7]. 2D materials, such as graphene WS₂, are subject to severe wear but have a very low coefficient of friction [8]. Antifriction



materials include transition metal oxides, h-BN and nitrocarbons, which have high wear resistance and a lower coefficient of friction compared to graphene. This behavior of 2D materials is related to the nature of the internal interlayer bond with each atomic layer. In low-friction 2D antifriction materials, the structural layers are held in place by weak van der Waals forces, which causes easy sliding between the layers and reduces friction. Two-dimensional metal oxides typically have a tetragonal or hexagonal structure in which atoms are covalently bonded to each other, causing high intralayer friction and reducing wear as they reduce gaps between layers. The coefficient of friction increases with increasing strength between the ball joints, which reduces the wear of 2D materials.

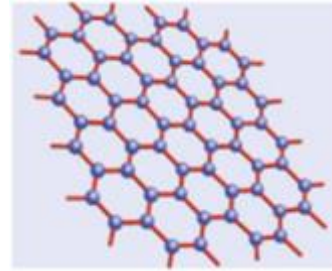
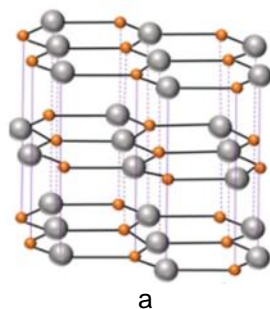
The most studied 2D materials are MoS₂ and carbon-based compounds, including graphite and graphene. The most well-known solid lubricant for aerospace engineering in dry conditions is MoS₂.

In fig. 1 shows a schematic representation of the most common solid antifriction materials.

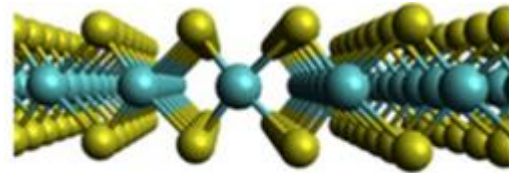
Friction can be quantified using the coefficient of friction and wear rate. To effectively study friction losses, it is important to understand the underlying mechanisms of friction losses at the atomic level. It is known that in the process of friction there is heat, which is released through various mechanical, physical and chemical interactions that occur at the interface of the sliding surfaces. At the same time, the complexity of the interactions of these phenomena and the lack of a theoretical model of the friction process complicates the quantitative and qualitative assessment of the contribution of these interactions.

Consider the sliding surfaces shown in Fig. 2 and their interaction.

Wear of sliding surfaces is caused by deformation and destruction of the upper layers of the part, which leads to its damage. Wear makes the surface rougher, which increases friction. For solid film lubricants, it is important that the lubricating film does not undergo brittle fracture, but plastic deformation. By changing the grain size and orientation in 2 D materials. it is possible to control the friction process.

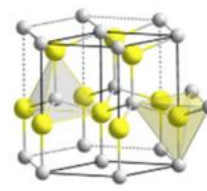


B



Mo S

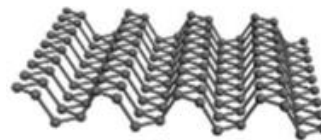
c



d



f



k

Fig. 1. Schematic image of various solid antifriction materials. a - boron-based mixtures, b - grafen, c - Sulphides and selenides of transition metals, d - ceramic materials with two-dimensional structure, f - composite materials, k - black phosphorus.

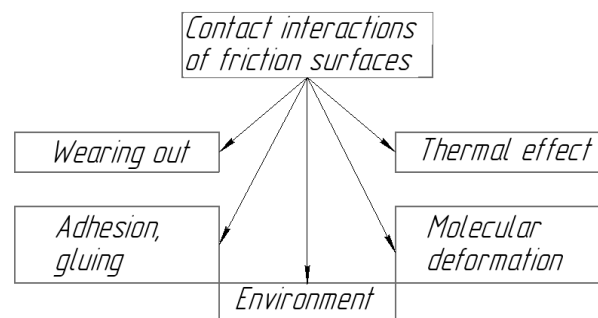


Fig. 2. Scheme of interactions of friction surfaces.

Under the action of friction forces, the molecules at the boundaries of the sliding surfaces collide with each other, and the interaction of the



surface atoms of the thin film with the atoms of the counterbody takes place. 2D materials are quite smooth and have low roughness. They are easily deformed or exfoliated depending on the strength of adhesion of the surface layer. This deformation of 2D layers due to the adhesion of atoms is known as atomic corrugation. Corrugation of atoms causes the deformation of molecules with the release of heat. Significant contact load leads to adhesion between atoms due to molecular deformation. To avoid this contact interaction, additional energy is required, which is released in the form of heat of friction. The presence of dislocations and inclusions increases the energy of corrugation, because energy is lost in the form of heat to overcome and move these defects. The higher the number of dislocation movements, the more heat is released due to molecular deformation.

At a certain temperature, molecules and atoms receive enough energy to move along the contact boundary. The speed of these oscillations can increase or decrease depending on the ambient temperature or the heat released due to friction in the contact zone, and also depends on the potential for interaction between atoms and molecules. When the interaction potential is large, the overall effect of thermal activation on heat release is slowed down, and more heat is required to create such effects. This is due to the thermal effect on the atoms, which facilitates sliding. The thermal effect of heat dissipation depends on the sliding speed and the roughness of the sliding surface.

Friction welding is one of the most important problems associated with increased friction due to chemical interactions in the contact area. Welding and bonding between surfaces can occur between friction surfaces. The formation and rupture of these bonds during movement between the friction surfaces leads to increased friction and accelerates the destruction and wear of the surface layer of parts.

The wear process causes the metal bonds to break and thus releases heat, as these reactions are exothermic. Surface oxidation and corrosion due to environmental influences are also exothermic and lead to the release of heat. The heat is released the higher the energy of the dissociation of the connection. The binding energy of different types of atomic bonds is presented in table 1.

Table 1. The energy of communication and melting point of different types of glue.

Type of gluing	Material	Communication energy (kcal/mol)	Melting point (°C)
Ion	NaCl	153	801
	MgO	239	1000
	Si	108	1410
Covalent	C	170	3550
	Hg	16	-39
	Al	77	660
Metallic	Fe	97	1538
	W	203	3410
Van Der Waals	Ar	1,8	-189
	Cl ₂	7,4	-101

The properties of solid antifriction materials depend on the environment. Chemical and physical interactions between solid antifriction material and the environment have a significant impact on its tribological characteristics.

Graphite is known for its antifriction properties, especially in humid environments. Moisture leads to a weakening between the van der Waals layered forces or broken bonds due to saturation with H⁺ and OH⁻ ions. Rough graphite is used as an additive to solid antifriction materials to improve their tribological characteristics, especially in humid environments.

Since the discovery of graphite mixtures, they have been recognized as a promising material that could revolutionize, particularly in the electrical industry. The tribological behavior of graphite mixtures is also influenced by their structure, the reactivity of different functional groups, chemical affinity for environmental species and the thickness of the surface layers.

The sliding friction on the surface of graphite mixtures depends on the thickness or number of atomic layers. As the number of layers increases, the friction force decreases and does not depend on the normal force, sliding speed and substrate material.

Analysis of antifriction materials showed that their application to the surface of parts can be carried out using the process of cold gas-dynamic spraying.

Analysis of antifriction materials showed that their application to the surface of parts can be carried out using the process of cold gas-dynamic spraying.

The scheme of installation for cold gas-dynamic spraying of antifriction surface layers is presented in Fig. 3. [9, 15].

According to the scheme (Fig. 3), compressed air is supplied through the hole 2, passes through the holes 3 with a heated nichrome spiral, in contact with which the air is heated to a given temperature and enters the air accelerator 6. As a result of accelerating



compressed air part of the pressurizer 6, the air pressure drops less than atmospheric, there is an ejection effect, due to which the channel of the nozzle 7 is absorbed spray metal powder and enters the jet of heated compressed air. Moving in the heated compressed air in the hole of the nozzle 7, the metal powder is heated and then transferred to the substrate forming a continuous coating.

By regulating the magnitude of the electric current and, accordingly, the heating temperature of the nichrome spiral and the flow rate of compressed air, it is possible to influence the heating parameters of metal powder particles and set the optimal modes of functional coating. The use of compressed air as a coolant creates safe working conditions.

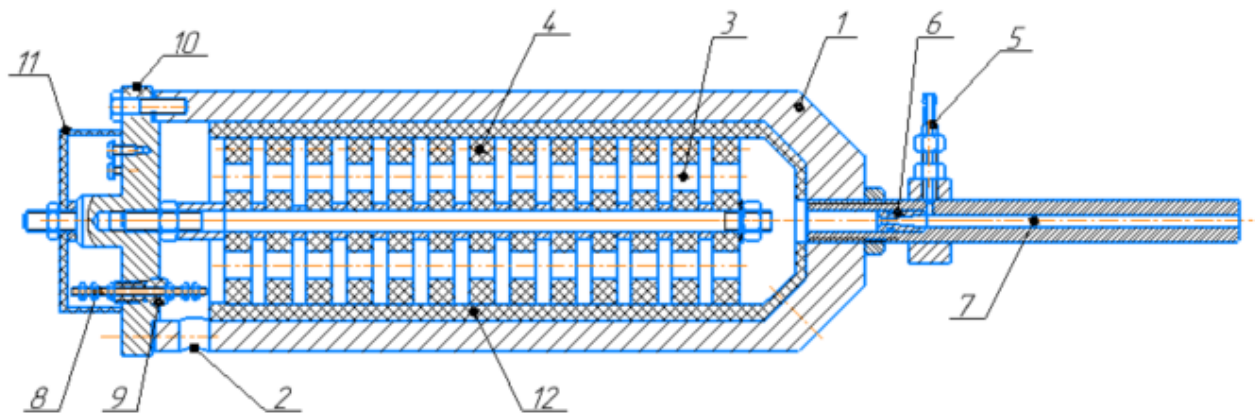


Fig. 3. Gas-dynamic spraying device:

- 1 - housing; 2 - hole for compressed air; 3 - openings; 4 - ceramic disks;**
- 5 - a branch pipe; 6 - air accelerator; 7 - nozzle; 8 - electrical contacts;**
- 9 - electrical insulators; 10 - crash; 11 - protective screen; 12 - thermal insulator**

Based on the scheme, an installation is created, which can maintain stable, regulated conditions for spraying powder materials.

Powder copper C01-00 and powder graphite with a particle size of 10.7 – 80.8 microns were used for the research. The content of powdered graphite was 5% of the total mass of the powdered copper-graphite mixture.

The installation for cold gas-dynamic spraying works as follows. Due to the effect of the ejection, the sprayed copper-graphite powder is fed into the airflow. Heated and dispersed powder in the airflow reaches the surface of the substrate and forms a solid layer of coating.

The amount of powder for one operation was 0,47 g. spraying distance – 10 mm. Aluminum plates AA7075-T651 with a thickness of 4 mm were used as a substrate. Before the study, the surface of the plates was not further processed.

The study was conducted on three different temperature regimes of compressed air. Temperature measurement was carried out using a thermocouple built into the nozzle. Adjusting and maintaining temperature were ensured with the help of a smooth current regulator. Air pressure was

maintained at a value of 0,5 MPa. The results of the spraying are shown in Figure 4.

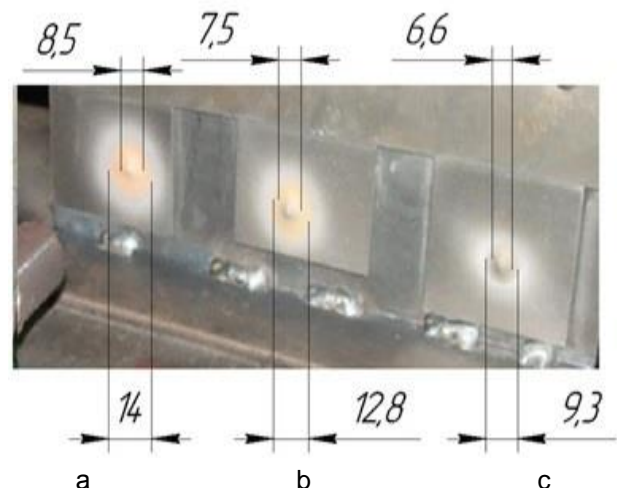


Fig. 4. Spraying figures: a – sample Number 3, b – sample Number 2, c – sample Number 1.

The substrate was weighed before and after spraying. All data were entered into Table 2, where, T, the spraying temperature, m_1 and m_2 are the mass of the substrate before and after spraying.

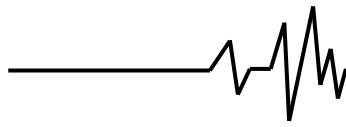


Table 2. The effect of spray modes on the powder utilization rate

Sample Number	T, So	M1, G	M2, G	MP, G	K, %
And	350	10,41	10,45	0,04	8,5
II	400	10,55	10,67	0,12	25,5
III	450	10,79	10,99	0,2	42,5

With the help of the application "Mass-centering characteristics" of the software "Compass-3D", the mass of the spraying figure as a solid composite material made of the copper-graphite mixture was determined. In the program "Compass-3D" designed 3D models of the resulting spray shapes by their real size (Fig. 5).

To determine the mass of spraying figures, it is necessary to know the density of the copper-graphite mixture. This density was determined taking into account the fact that one cubic meter contains 95% copper with a density of 8990 kg / m³, which is 8540.4 kg and 5% graphite density of 2100 kg / m³, which is 105 kg, so 1 m³ of the copper-graphite mixture will weigh 8540,4 + 105 = 8645,4 kg, and the density of such a mixture is ρ₁ = 0,0086454 g / mm³.

The density of the coating ρ₂ was defined as the ratio of the mass of the weighted spray figure to its

calculated volume obtained from the 3D model using the "Mass-Centering Characteristics" application of the Compass-3D software.

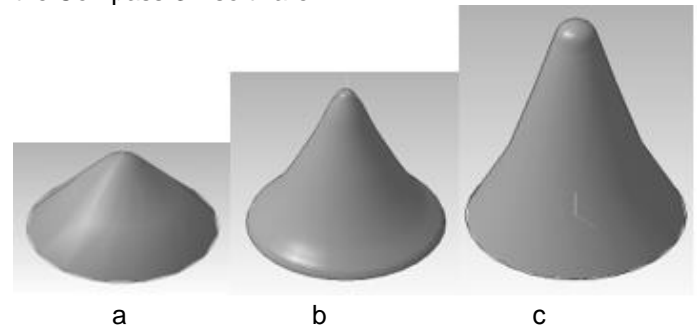


Fig. 5. 3D models of spraying figures, a – sample No 3, b – sample No. 2, c - sample Number 1

The porosity of the resulting J spray shapes was determined by the formula:

$$J = \frac{\rho_1 - \rho_2}{\rho_1} \cdot 100\% \quad (1)$$

Thus, the proportion of air in the volume of the spraying figure was determined.

The results of determining the porosity of the spraying figures are presented in Table. 3.

Table 3. Determine the porosity of spray shapes

Sample Number	The estimated mass of the spray figure for copper-graphite powder, g	Estimated volume, mm ³	Weighted mass of the spraying figure, g	Density spray shapes ρ ₂ , g/mm ³	Porosity spray shapes J, %
I	0,24724	36,206894	0,04	0,006829	21
II	0,34965	84,275364	0,12	0,00415	52
III	0,5914	162,907247	0,2	0,00363	58

In the course of the study, it was found that compared to the material of the substrate AA7075, the friction coefficient on the steel of which is 0,5, friction coefficient for copper-graphite surface layer on the same steel for sample No. 3 was reduced by 47% for sample No. 2 by 57%, for sample No. 1 by 62% This improvement in tribological characteristics allows to form microfilms of solid powder materials with the addition of graphite by cold gas-dynamic spraying on worn surfaces of parts agricultural machinery and machinery for other purposes. Given that these coatings have significant porosity, this opens up additional opportunities in improving the antifriction properties of the functional porous coating by impregnating pores with various lubricants.

One of the directions of creating surface layers of parts with increased tribological characteristics using gas-dynamic spraying is the creation of composite coatings [10 - 13]. the specified content of the components in the coating.

To obtain composite copper-aluminum coatings on a steel substrate, a mechanical mixture of copper powder C01-00 and aluminum A30-01 was

used. In Fig. 6 photos of these powders are shown. For the study, the following modes of operation of the gas-dynamic spraying device were selected: air pressure R₀ = 0,6 MPa, ejection pressure Re = 0,095 MPa, heating temperature of compressed air at the entrance to the nozzle T₀ = 300±10 °C, spraying distance 20 mm.





b

Fig. 6. Photos of powders sprayed: a) aluminum powder A 30-01, b) copper powder C01-00

The size of powder particles is one of the most important parameters that determine the possibility of its use in cold gas-dynamic spraying. The size of these particles largely depends on the quality and properties of the coatings obtained.

The average values of particle size d_{cp} and the standard deviation S_d , calculated by micrographs shown in Fig. 7, are presented in Table. 4. The maximum share by volume (mass) is occupied by particles of 20-52 microns for aluminum and 42 - 78 microns for copper.

Table 4. Powder parameters

Powder	$d_{cp}, \mu m$	s_d, mkm
30-01	3 0,3	15,8
From 01-00	4 6,4	26,6

To create composite coatings, mixtures of copper and aluminum powders were prepared in the proportions shown in Table. 5. The total weight of the portion of the mixture for one spray was 0,5 grams.

aluminum and copper in the sprayed coating were calculated by the measured coefficient of spraying the mixture and the results of the elemental analysis of samples on an electron microscope.

The coefficients of spraying separately

Table 5. Parameters of the mixture of powders

Powder	Mix number										
	1	2	3	4	5	6	7	8	9	10	11
From 01-00	1	0,9	0,8	0,7	0,6	0,5	0,4	0,3	0,2	0,1	–
30-01	–	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

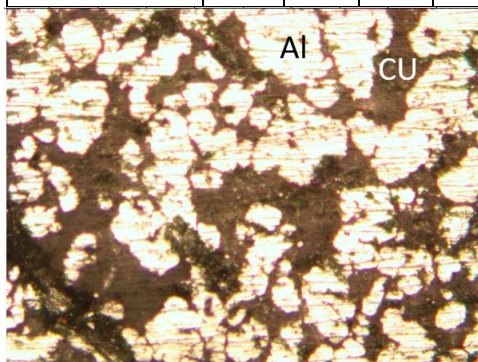


Fig. 7. Micrograph of the grind of the substrate with a composite coating copper – aluminum.

Micrographs obtained on an electron microscope were processed using photoM 1.21 and determined the area of the content of each of the components, that is, copper and aluminum. The photo of the processed microsliff is shown in Fig. 8.

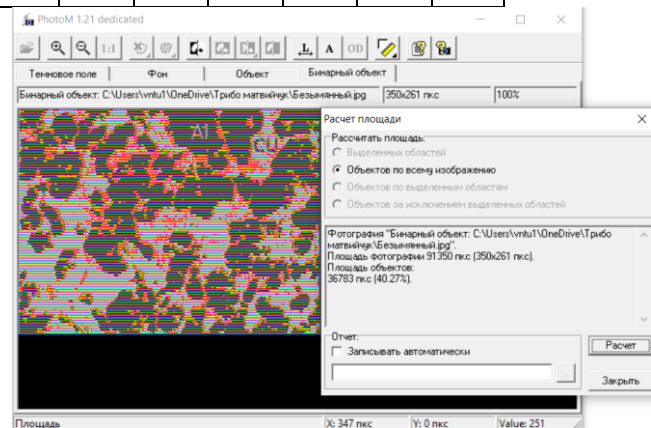


Fig. 8. The results of processing the micrograph of the grind with composite copper-aluminum coating using photo M 1.21, and the calculation of aluminum and copper content.

On Fig. 9 and 10, the results of calculations on the mass content of aluminum and copper in the coating (designated as C_{cAl} and C_{cCu} , respectively)



depend on their mass content in the original powder (designated as C_{pAl} and C_{pCu} , respectively) dotted lines.

$$y = 79,003x^6 - 214,09x^5 + 199,99x^4 - 71,815x^3 + 7,338x^2 + 0,5835x - 0,001 \quad (2)$$

where x is C_{pAl} , and y is C_{cAl} .

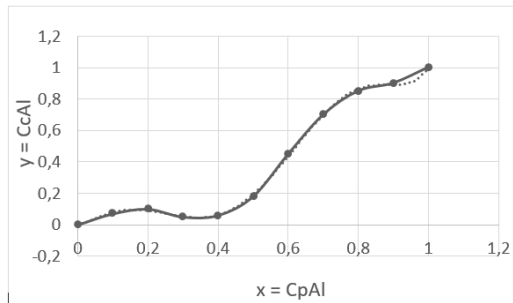


Fig. 9. The absolute value of the aluminum content in the coating C_{cAl} , depending on its content in the source powder C_{pAl}

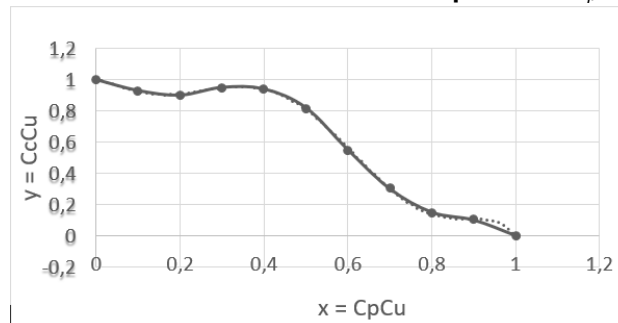


Fig. 10. The absolute value of the copper content in the coating of C_{cCu} , depending on its content in the original powder C_{pCu}

$$y = -79,003x^6 + 214,09x^5 - 199,99x^4 + 71,815x^3 - 7,338x^2 - 0,5835x + 1,0014. \quad (3)$$

where x is C_{pCu} , and y is C_{cCu} .

The patterns of change of coefficients of spraying are analyzed. In Fig. 11 shows a change in the spraying coefficients of the mixture of copper and aluminum 1, only aluminum 2, and only copper 3 from the absolute mass content of aluminum in the original powder mixture. Spraying coefficients are calculated by the content of aluminum and copper in the coating according to the formulas (4):

$$k_{dAl} = \frac{C_{cAl}}{C_{pAl}} k_{dmix},$$

$$k_{dCu} = \frac{C_{cCu}}{C_{pCu}} k_{dmix} \quad (4)$$

where – the coefficient of spraying a mixture of powder aluminum and copper. k_{dmix}

k_{dAl} – powder aluminum spraying factor.

k_{dCu} – powder copper spraying coefficient.

The obtained results for the coefficient of spraying the powder mixture of copper and aluminum are quite well approximated by parabola 4

(Fig. 11). Dash line 5 shows the approximation of the powder copper spraying coefficient, and 6 - the coefficient of powder aluminum spraying. It is clearly seen that at the initial concentration of aluminum, which is less than 66%, the coefficient of spraying powder copper is higher than the coefficient of spraying powder aluminum. Both coefficients gradually increase with an increase in aluminum concentration until it reaches a value of 61%. At concentrations of aluminum of more than 66%, the coefficients of copper and aluminum spraying approach each other and coincide with the coefficient of spraying the mixture.

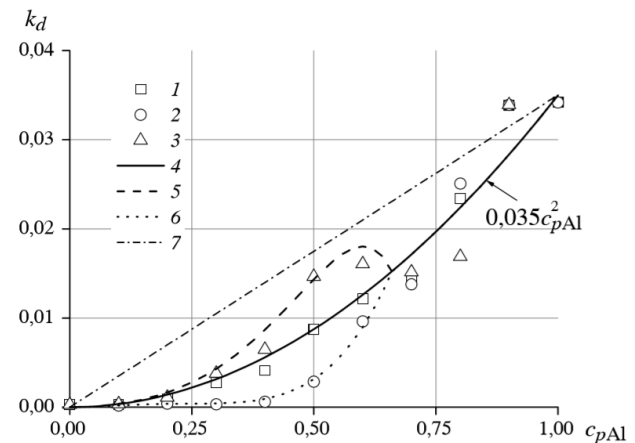


Fig. 11. Dependence of the coefficients of spraying the mixture: 1 – aluminum, 2 – copper, 3 – on the concentration of aluminum in the original mixture; 4 – parabolic approximation of the coefficient of spraying the mixture; 5 – approximation of copper spraying coefficient; 6 – approximation of aluminum spraying coefficient; 7 – coefficient of spraying the mixture according to linear theory (when the components do not affect each other).

The obtained data on the residual content of the components in the coating allows you to choose the composition of the original powder necessary to obtain the specified content of the components in the coating. For example, the maximum residual content of copper (~ 95%) can be obtained by adding 30-40% aluminum to the original powder. At this initial concentration of aluminum, the copper spraying factor will be 0.033%, which is significantly higher than the coefficient of pure copper spraying (0.01%). If, for example, you need to get a residual copper content of 50%, then it is necessary to add 61% aluminum to the original powder. In this case, the coefficient of copper spraying will increase markedly and will already be 15%, etc.

From this study, we can conclude that in the process of spraying, the components of the mixture affect each other. Presumably, the mechanism of interaction of components is that they are with different probabilities fixed on the surface, which



consists of different materials (that is, the probability of fixing copper particles on the surface of aluminum particles is higher than the probability of fixing copper particles on the surface of steel or copper particles themselves).

Conclusions. The analysis of antifriction materials is carried out, their advantages and disadvantages are shown. The design and type of installation for cold gas-dynamic spraying of antifriction surface layers are described. Copper-graphite powder with a particle size of 10,7 – 80,8 μm was used for the research. The possibility of creating porous copper-graphite coatings and composite copper-aluminum coatings with high antifriction characteristics using cold gas-dynamic spraying is shown. The coefficient of friction for the copper-graphite surface layer on steel for sample №1 was reduced by 47% for sample №2 by 57%, for sample №3 by 62% compared to the uncoated part.

Samples with composite coatings from mixtures of powders of aluminum and copper for different initial concentrations of aluminum (from 0 to 100% in increments of 10%) were obtained. All other things being equal (air pressure 0,6 MPa, wind heating temperature 300 °C).

The sputtering coefficients of the powder copper-aluminum mixture and the residual content of copper and aluminum in the obtained coatings were measured. Regularities of the content of components in the coating that allow you to choose the composition of the initial powder required to obtain a given content of components in the coating.

The obtained results confirm the possibility of creating a variety of antifriction coatings on friction pairs using cold gas-dynamic spraying, which can be recommended to improve the tribological characteristics of the components of machines and mechanisms.

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СТВОРЕННЯ ПОВЕРХНЕВИХ ШАРІВ ДЕТАЛЕЙ З ПІДВИЩЕНИМИ ТРИБОЛОГІЧНИМИ ХАРАКТЕРИСТИКАМИ ІЗ ЗАСТОСУВАННЯМ ХОЛОДНОГО ГАЗОДИНАМІЧНОГО НАПИЛЕННЯ

Однією із перешкод на шляху інтенсифікації виробничих процесів є відносно мала стійкість деталей вузлів обладнання цих виробничих процесів. Мала стійкість деталей виникає, насамперед, у парах тертя, особливо тих, що працюють із значним навантаженням в агресивних середовищах. Зношення поверхневих шарів деталей можуть руйнувати обладнання, та призводити до



втрат енергетичних та матеріальних ресурсів. Одним з шляхів вирішення вказаної проблеми є створення на поверхнях тертя функціональних покриттів стійких в агресивних середовищах. Наведено результати аналізу антифрикційних властивостей матеріалів які містять мідь, олово, свинець, алюміній, та полімери. Показано переваги і недоліки антифрикційних властивостей розглянутих матеріалів, а також можливість їх нанесення на поверхні деталей із застосуванням холодного газодинамічного напилення. Проаналізовано використання рідких і твердих антифрикційних матеріалів в якості мастил. Прیدілено увагу матеріалам з кристалічною структурою подібною до структури графіта, відомим як 2D-структури (двовимірні матеріали). Найбільш вивченими 2D-матеріалами є MoS_2 і з'єднання на основі вуглецю, включаючи графен і графіт. Показана схема взаємодії ковзних поверхонь, що включає молекулярну деформацію, знос, склеювання, тепловий ефект і вплив навколишнього середовища. Показано, що нанесення на поверхню деталей антифрикційних матеріалів можна здійснювати з використанням холодного

газодинамічного напилення. В статті показана схема і вид установки для холодного газодинамічного напилення поверхневих шарів за допомогою порошкових антифрикційних матеріалів. Для проведення досліджень було використано мідно-графітовий порошок з розміром частинок 10,7 – 80,8 мкм. Було встановлено, що порівняно з матеріалом підкладки AA7075, коефіцієнт тертя ковзання напиленого покриття з використанням мідно-графітового порошку знизився на 47% - 62%. Отриманні композиційні покриття з механічної суміші порошку алюмінію A30-01 і міді C01-00. Отримано залежності коефіцієнтів напилення алюмінію і міді від вмісту алюмінію в композиційній суміші, яка напилюється. Коефіцієнт напилення міді виявляється вище коефіцієнта напилення алюмінію. Обидва коефіцієнти монотонно збільшуються із зростанням кількості алюмінієвого порошку, поки вона не досягне величини 61 %. При більш високих концентраціях алюмінію (більше 66%) коефіцієнти напилення алюмінію, міді і їх суміші збігаються.

Ключові слова: антифрикційні матеріали, холодне газодинамічне напилення, антифрикційні покриття.

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