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Analysis of the Characteristics of Powder Self-Lubricant Composites by the Criteria of Antifriction, Wear Resistance and Strength

Vadim KOVTUN[1], Vladimir PASOVETS[1,2], Yordan MIRCHEV[3]

[1] University of Civil Protection of the Ministry for Emergency Situations of the Republic of Belarus, Minsk, Belarus, e-mail: vadimkov@ya.ru

[2] State research and production powder metallurgy association National Academy of Sciences of Belarus, Minsk, Belarus, e-mail: vladimirnp@ya.ru

[3] Institute of Mechanics of the Bulgarian Academy of Sciences, Sofia, Bulgaria, e-mail: mirchev@imbm.bas.bg, nntdd@abv.bg

Abstract
Tribotechnical and physico-mechanical characteristics of the developed composite materials based on powder systems "copper – polytetrafluoroethylene – carbon nanostructures" are presented in this article. A comparative analysis of the characteristics of the developed materials with known composite materials has been performed.

Keywords: powder composite materials, friction units, tribotechnical characteristics, friction coefficient, wear rate, strength.

1. Introduction

One of the main tasks of modern materials science is the development of new antifriction composite materials that provide stable operation of friction units of machines and mechanisms for various purposes without liquid or grease lubricants [1]. At the same time, it is necessary to pay attention to the relevance of the problems associated with increasing the reliability and durability of modern machinery. This is due to the negative influence of friction and wear processes on the surfaces of contacting parts [2].

A number of composite materials for the manufacture of parts of friction units are described in the technical literature. Composite materials based on a metal matrix are now widely used. These materials contain functional fillers for various purposes [3]. Graphite [4], molybdenum disulphide [5], boron nitride [6] are used to improve the antifriction properties of composites for friction units. Composites based on a metal matrix with a polymer filler are popular in the industry. For example, materials DU, DP and DX [7]. Multicomponent solid materials containing nanosized components are replacing known composites [8]. Fullerenes [9], carbon nanotubes (CNT) [10], and onion carbon nanostructures (ONS) [11] are widely used as nanosized fillers.

The relevance and importance of the issues of saving metals in the production of composite materials is beyond doubt. Powder metallurgy is a progressive technology that can significantly reduce metal consumption in the production of parts for various purposes. In the production of parts of friction units by powder metallurgy methods, significant savings can be obtained by reducing metal losses. And the use of the electrocontact sintering method, which makes it possible to vary the component composition of powder composites over a wide range, makes it possible to form the properties of materials that are unattainable using traditional methods of sintering in furnaces [12].

Thus, it is necessary to consider questions concerning the comparison of the strength and wear resistance characteristics of both traditionally used antifriction materials and new composites containing a nanosized filler in their composition. The purpose of the study was to compare the tribotechnical and physico-mechanical characteristics of traditionally used composite materials and the developed powder composite materials for friction units without lubrication.

2. Materials and investigation methods

In the work, electrolytic copper powder PMS-1 All-Union State Standard 4960–2017 was used as a metal matrix of the developed composites. A mixture consisting of 20% CNT and 80% ONS was used as a nanosized filler of the metal matrix. Polytetrafluoroethylene (PTFE) powder clad with a copper sheath with a thickness of 5 to 7 µm, was used as a polymer filler of the metal matrix.

The distribution of the nanosized filler during the preparation of nanocomposites was carried out in the process of mechanical activation by two-stage preparation of the powder mixture. At the first stage, mechanical activation of the copper-carbon nanostructures powder system was carried out; at the second stage, this powder system was mixed with clad PTFE [13]. The use of a two-stage preparation of a powder mixture is due to the possibility of preserving the hereditary structure of clad PTFE [14].

Consolidation of the initial components of the developed composites was carried out on a pilot plant, made on the basis of the resistance welding machine with electrodes-punches. The samples were formed by pre-pressing at a pressure of 400 MPa and sintered by passing an electric current with a density of 400 A/mm^2 for 1.5 seconds.

Coatings from the developed composite materials were obtained on a copper tape by electrocontact sintering. The coating was carried out on a setup based on a contact welding machine with roller electrodes. As a result, the powder layer was sintered to the copper tape at a pressure of 300 MPa, a current density of 300 A/mm^2, and an electrode displacement speed of 0.4 m/min.

Tribotechnical tests were carried out by sliding friction according to the "shaft – bearing half-liner" scheme at a load of 1.5 MPa, a sliding speed of 1.5 m/s and a temperature of 20 °C. The material of the counterbody is carbon steel 1.1191 with a surface roughness of Ra = 0.3–0.4 µm. Samples were degreased in acetone before testing. The running-in was carried out at a load of 100 kPa until full contact was formed over the entire friction surface. The wear rate was determined for the regime of steady friction without lubrication. The compressive strength was determined on an Instron 5567 universal testing machine (USA). The porosity of the sintered composite materials was determined by hydrostatic weighing. The physico-mechanical and tribotechnical characteristics of the currently used composite materials for friction units are taken from open sources.

To conduct a full and comprehensive comparative analysis of composite materials and coatings, certain criteria were formed, on the basis of which a comparison was made:

1) antifriction, characterized by a coefficient of friction;

2) wear resistance, characterized by wear rate;

3) strength, characterized by compressive strength and Young's modulus.

3. Results and discussion

A set of experimental studies of the physico-mechanical and tribotechnical characteristics of the developed composites for friction units without lubrication has been carried out. An analysis of the research results made it possible to establish a mechanism for increasing the wear resistance of composite materials. The mechanism for increasing the wear resistance of composite materials is that during friction without lubrication, the PTFE contained in the material allows the formation of separating layers on the friction surface, which helps to reduce the friction coefficient to 0.1–0.13 and the friction force in contact, minimizing the period of running-in parts of friction units and increasing the allowable load on the friction unit (pressure up to 1.5 MPa and sliding speed up to 1.5 m/s). When the PTFE layers are destroyed in the process of friction, the carbon nanostructures distributed in the volume of the metal matrix come to the surface as the material wears out, make a specific movement along the friction surface of the material, and prevent the development of setting processes during the interaction of microroughnesses of the contacting surfaces of the material and the counterbody, which makes it possible to reduce the wear rate material up to 0.06–0.07 µm/km.

The results of experimental studies are presented in Table 1. Table 1 and also shows the modes of tribotechnical tests (sliding speed and pressure).

Table 1. Tribotechnical and physico-mechanical characteristics of powder composite materials for friction units without lubrication

Material (country), "composition of the material"	Friction coefficient	Wear rate, µm/km	Sliding speed, m/s / Pressure, MPa	Compressive strength, MPa	Porosity, %
PA-DGr10, (USSR), «Cu +10 wt.% Gr» [16]	0.15–0.20	0.5–0.55	10 / 0.025	–	2–9
CuG15 (Russian Federation), «Cu + 15 wt.% Gr» [17]	0.22–0.26	1.46–1.5	1 / 1	135–175	3–5
RU 2024639 (Russian Federation), «Cu + 2 wt.% Gr + + 5 wt. % Sn + + 1 wt. % CaF_2 + + 5 wt. % PN85Yu15» [18]	0.1–0.12	0.19–0.21	2.5 / 1.5	–	–
DN5M3KF9 (Ukraine), «Cu + 5 wt. % Ni + + 3 wt. % Mo + + 9 wt. % CaF_2» [19]	0.16	30	60 / 7	177–183	2–4
DE10 2004 011 831 (Germany), «Cu + 7,41 wt. % Gr + + 12,04 wt. % Sn + + 1,85 wt. % Pb + + 0,93 wt. % CuP» [20]	0.2	8.3	0.008 / 10	230	–
Developed composites, «Cu + 6 wt. % PTFE + + 0,07 wt. % (CNT + + ONS)»	0.1–0.13	0.06–0.07	1.5 / 1.5	156–165	2–4
Remarks: Gr – graphite, PN85Yu15 – intermetallic (chemical compound Ni and Al)					

At the same time, in order to justify the choice of the developed materials for operation in friction units operating without lubrication, it is necessary to consider the existing analogues. One of the most popular in the industry is an antifriction powder material based on copper PA-DGr10 All-Union State Standard 26719-85, intended for parts of friction units of machines and mechanisms and containing 9–11 wt. % carbon as graphite. This material is a copper matrix with evenly distributed inclusions of graphite and can be used for operation without lubrication at high sliding speeds – up to 50 m/s [15].

The material presented in [18] has been developed for the manufacture of self-lubricating plain bearings operating in dry and semi-dry friction modes. The rubbing surfaces in the semi-dry friction mode are in full contact or in long areas, and there is no separating lubrication layer. This material can be used in friction units of electric motors in the radio engineering and electronic industries, household appliances, in friction units of textile machines, etc., operating in the range of specific pressures up to 1.5 MPa and sliding speeds up to 25 m/s. The composite material is made by powder metallurgy by pressing at a pressure of 170–200 MPa, followed by sintering in an endogas medium at a temperature of 750–850 °C. Intermetallic compound PN85Yu15 is introduced to form secondary structures in the friction zone, which level the roughness of mating surfaces. Calcium fluoride CaF2 and graphite are used as solid lubricants.

Composite material for friction units based on copper DN5M3KF9 is presented in [19]. This composite is designed to operate in friction units at speeds from 200 to 400 rpm. Samples of material DN5M3KF9 were produced by powder metallurgy by three-stage mixing for 4 hours, pressing at a pressure of 400–450 MPa, and sintering at a temperature of 82–870 ºC. The three-stage preparation of the initial components made it possible to avoid the segregation of individual powders in the composition. The minimum residual porosity was obtained by calibration at a specific pressure of 840 MPa and annealing at t = 450 ºC for 1 hour in a hydrogen atmosphere.

Sintered material based on powdered copper for the manufacture of plain bearings is presented in [20]. This material contains 10–15 wt. % tin, 0.5–10 wt. % bismuth and 5–12 wt. % graphite in a copper matrix [20]. In this case, graphite with a grain size of <40 µm is preferred. Also 1–3 wt. % molybdenum disulfide or 0.5–2 wt. % copper phosphide is desirable to introduce into the composition of the material to improve sintering. This composite material is used in industry for the manufacture of radial and thrust bearings, as well as anti-friction bushings and sliding plates.

Composite materials for tribotechnical purposes used in the form of coatings are also of considerable interest. These materials include MU and Fritex composites manufactured by Technymon (Italy), as well as DU and DP composites manufactured by GGB Bearing Technology (UK).

The MU material (Table 2) is constructed in layers and consists of a layer of PTFE and molybdenum disulfide with a thickness of 0.01–0.04 mm, a layer of sintered bronze with a thickness of 0.20–0.35 mm, a steel base with a thickness of 0.25–2.70 mm. This composite is intended for the manufacture of anti-friction bushings and thrust washers, as well as other special products that operate at temperatures from -200 °C to +280 °C. The maximum allowable sliding speed in dry friction is 2.5 m/s [21]. The use of liquid lubricants makes it possible to increase the maximum allowable sliding speed of this material up to 10 m/s. The service life of the MU material is determined by the values of the PV-factor. The long service life of this material is only possible at values of PV-factor from 0.2 MPa m/s to 1.8 MPa m/s. Values of PV-factor from 2.5 MPa m/s to 3.6 MPa m/s are only acceptable for short periods of material operation. The material has a low coefficient of friction 0.15–0.2 at a sliding speed of 0.5–2.5 m/s and a pressure of 1 MPa. In friction pairs with this material, it is necessary to avoid the use of bronze and aluminum, as well as materials with a surface roughness of more than 0.4 microns.

Composite material Fritex-B is intended for the manufacture of anti-friction bushings, which are operated at temperatures from -100 °C to +260 °C. Fritex-B is a support layer made of CuSn8 bronze with a thickness of 0.50–2.70 mm, on which an anti-friction PTFE layer is applied. The value of the friction coefficient is 0.15 at the maximum allowable sliding speed with dry friction (1.5 m/s) and a pressure of 1 MPa (Table 2) [22].

Table 2. Properties of metal-polymer powder coatings

Material (manufacturer), powder system	Friction coefficient	Wear rate, μm/km	Testing regime		PV-factor, MPa m/s
			Sliding speed, m/s	Pressure, MPa	
MU (Technymon, Italy), "bronze – PTFE – molybdenum disulfide" [21]	0.15–0.,2	0.1–0.12	1.5	1.0	1.8
Fritex-B (Technymon, Italy), "bronze – PTFE – graphite" [22]	0.1–0.15	0.09–0.11	1.0	1.0	–
DU (GGB Bearing Technology, UK),"bronze – PTFE – lead" [23]	0.1−0.16	0.12−0.15	0.5	1.0	1.75
DP4 (GGB Bearing Technology, Великобритания), "bronze – PTFE" [24]	0.22−0.25	0,13−0,16	1.0	1.0	1.0
Developed coating, «Cu + 6 wt. % PTFE + + 0,07 wt. % (CNT+ONS)»	0.1–0.13	0.06–0.07	1.5	1.5	2.25

Composite materials DU and DP4 are widely used. The DU material consists of a steel base that provides heat dissipation from the friction surface and the necessary stiffness. This steel base is coated with a porous bronze layer 0.25 mm thick impregnated with a mixture of PTFE and lead. The impregnated bronze layer is topped with a final layer of 0.025 mm thick PTFE and lead. DU material is used at temperatures from -200 °C to +280 °C. With dry friction, the PV factor is 1.75 MPa m/s, and the maximum allowable sliding speed is 2.5 m/s. The coefficient of friction of the DU material is 0.1–0.16 at sliding speeds above 0.2 m/s [23]. The known material DP4 has a construction similar to that of DU. DP4 does not contain lead. The operating temperature range of DP4 material is also from -200 °C to +280 °C. The maximum allowable sliding speed of this material is 2.5 m/s in dry friction. The PV-factor is 1 MPa m/s. The coefficient of friction of the DP4 material at a sliding speed of 1 m/s and a pressure of 1 MPa is 0.22–0.25 (Table 2) [24]. DP4 has an advantage over DU in lead corrosive environments.

Table 2 also presents the tribotechnical characteristics of coatings made on the basis of the developed composite materials.

4. Conclusions

The results of experimental studies of the developed composite materials based on a copper matrix filled with a metal-clad polymer and carbon nanostructures are presented in this paper. A comparative analysis of the tribotechnical and physico-mechanical characteristics of the developed composite materials with known and widely used in industry composites has been performed. Comparison of the developed composite materials was carried out with known composite materials PA-DGr10 and DN5M3KF9. The characteristics of the coatings made from the developed composite materials are compared with the widely used DU, DP4, Fritex-B, MU. It is shown that the developed composite materials based on powder systems "copper – copper-plated PTFE – carbon nanosized filler" are at the level of the best foreign analogues in terms of anti-friction, wear resistance and strength.

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