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# REVEALING PATTERNS OF CHANGE IN THE TRIBOLOGICAL EFFICIENCY OF COMPOSITE MATERIALS FOR MACHINE PARTS BASED ON PHENYLONE AND POLYAMIDE REINFORCED WITH ARIMIDE-T AND FULLERENE

*The object of the study is the process of changing tribological efficiency according to tribotechnical characteristics (wear intensity, friction coefficient, temperature in the contact zone) of composites based on phenylone C-1 and polyamide PA-6 with arimide-T filler and fullerene C-60. The study solved the problem of obtaining composites with high wear resistance.*

*Based on the results of research, it was found that varying the content of arimide-T makes it possible to obtain composites with different patterns of changes in tribotechnical characteristics under conditions of dry friction, lubrication with water and I-50 oil. Composites with the composition: phenylone C-1+15 wt. have the maximum tribological efficiency. % arimide-T+3 wt. % fullerene C-60 and polyamide PA-6+30 wt. % arimide-T+3 wt. % fullerene C-60.*

*Phenylone C-1 has destructive properties when working in the environment of water and temperature in the friction zone. Its reinforcement with arimide-T and fullerene C60 gave positive results of a complex of tribotechnical characteristics under these conditions. It was found that the wear of composites based on phenylone C-1 in I-50 oil is two orders of magnitude lower than in water. Research of samples from the obtained composites based on phenylone C-1 and polyamide PA-6, reinforced with the optimal content of arimide-T and fullerene C60, showed that their wear resistance when lubricated with oil is 3.5...4.0 times greater than the wear resistance of bronze.*

*An applied aspect of the reported results is the introduction of manufacturing technologies and restoration of machine parts from the proposed composites. It has been proven that their optimal composition contributes to high tribological efficiency and could provide the required level of wear resistance and reliability of resource-determining nodes, systems, and machine assemblies.*

*The results could be used by machine-building and repair-technological enterprises*

*Keywords: phenylone, polyamide, arimide, composite, wear, intensity of wear, coefficient of friction, temperature*

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## 1. Introduction

The evolution of mechanical engineering shows that it is economically feasible to design composite materials based on polymers, which serve as a basis (matrix) and are characterized by the availability of production capacities [1]. This primarily concerns aliphatic and aromatic polyamides, which can be used to replace metals and alloys, especially non-ferrous ones. Polyamides are characterized by high strength and can be used in combination with any materials. At the same time, their wear is reduced by 1.5...2.0 times compared to non-ferrous metals. The manufacturing time and cost of parts made of polymers are relatively small, compared to products made of steel and bronze.

Machine parts made of polymers work under extreme conditions. They are operated under heavy loads, a wide temperature range and under conditions of intense friction and wear. And therefore, they need reinforcement and production of polymer composites for structural purposes. When designing such composites, both aliphatic polycaproamide – polyamide 6 PA-6, and aromatic polyamide – phenylone C-1 are used as a matrix.

The introduction of dispersed or fibrous fillers in polyamides, as in matrix materials, significantly increases the operational properties (wear resistance) and characteristics of the coupling of parts (wear intensity, friction coefficient, temperature in the contact zone, tribological efficiency) and expands the possibilities of their application. This is relevant because the high wear resistance of materials provides for a high level of operational reliability of parts, assemblies, systems, and machines as a whole.

## 2. Literature review and problem statement

The use of dispersed fillers significantly improves a number of properties and characteristics of polyamide PA-6 and phenylone C-1 [2].

In [3], it was established that the introduction of silica gel into phenylone C-1 at compression by 6.3 % and 13.3 % leads to an increase in stress, yield strength, or modulus of elasticity. The results of the research make it possible to optimize the system of tolerances and fits of parts made of polymer composite, to simplify the technology of their manufacture and, as a result, to reduce their cost. Depending on the content of the filler, the heat resistance of the composite increases by 11.6 % while its thermal linear expansion of the composite decreases by 10...20 %. It is not stated how these results contribute to the improvement of the tribotechnical characteristics of the materials.

Aliphatic and aromatic polyamides were used as the matrix of composites in work [4] while finely dispersed metal powders were used as fillers. This makes it possible to increase the strength characteristics by almost 1.5 times and wear resistance by 2.5...4.0 times. At the same time, among the specified fillers, composites with a filler with carbonyl nickel have the maximum wear resistance. The positive effect in this case is performed by carbon, which creates conditions for solid lubrication. At that time, there was no study of the tribological efficiency of the obtained compositions. The dependence of the tribotechnical characteristics on the performance criterion has also not been established.

In work [5], it was found that the polymer composite based on polyamides and kaolin improves tribological properties under conditions of dry sliding friction. The wearability of the polymer composite when sliding in water was investigated. It was shown that the addition of kaolin to PA-6 worsens the degree of crystallinity and plasticization of the polymer composite, as a result of which surface wear increases during sliding friction. At the same time, there is a decrease in the coefficient of friction. The authors should have explained the reported research results.

The effect of GNP graphene nanoplates on the mechanical and tribological properties of polyamide PA-6 was studied in [6]. The tribological behavior of the composites was studied using a piston tribometer according to the “ball-disk” scheme. The addition of GNPs to the PA-6 matrix significantly improved the mechanical and tribological properties. The effectiveness of this polymer composite was proven by improving the Young’s modulus, microhardness, and scratch resistance, but it was also necessary to take into account the tribotechnical characteristics of the material, which are important in the operation of machine parts.

In work [7], molybdenum disulfide $MoS_2$ was introduced as a filler into PA-6 matrices as a special solid lubricant. The resulting polymer composite has a low coefficient of friction of 0.15...0.30 on steel. Bearings, bushings, locking plates and guides are made from this composite. At the same time, PA-6, filled with a special solid lubricant, demonstrated the best tribological properties among plastics. The lowest coefficient of friction was observed, as well as the highest wear resistance and acceptable limits of the tribocoupling performance criterion *pv* (the product of the specific load and the sliding speed). It is shown that the introduction of solid lubricants has a positive effect on the wear resistance of the polymer composite in all aggressive environments. The most priority use of polymer composite parts was found to be their operation in alkaline environments. The work requires further studies into the influence of molybdenum disulfide content on the tribotechnical characteristics of the resulting composites.

To improve the properties of polyamides, in [8], ultradisperse powder fillers based on silicon nitride are also introduced into their composition. These include the ultra-dispersed powder of silicon-yttrium oxynitride, which was obtained by the method of plasma-chemical synthesis in the amount of 0.2...10 wt. %. It has been proven that ultradispersed fillers of this type significantly improve the properties of polymer composites based on polyamides due to their high specific surface area (45...60 $m^2/g$), refractoriness, and resistance to oxidation when heated in air. It is shown that the content of fillers in small quantities is the most effective due to their significant influence on the process of structure formation in the volume of the polymer. The influence of the filler content on the tribotechnical characteristics of the composite is not specified.

In work [9], it is noted that in order to achieve the best properties of composites, the content of the investigated fillers (graphite, molybdenum disulfide, and boron nitride) introduced into phenylone should not exceed 5 wt. %. At the same time, the maximum increase in the tribological properties of the polymer composite is observed. A further increase in the filler content increases the wear and friction coefficient of the polymer composite but to this end, appropriate studies should be carried out.

In [10], a set of basic thermophysical, physical-mechanical, and tribological properties of composites based on phenylene with a filler of graphene nanoplates is considered. It was found that the introduction of graphite into phenylone significantly improves its tribotechnical characteristics. Under the dry friction mode, the friction coefficient decreases by 4.6 times. At the same time, the intensity of linear wear is also significantly reduced. Graphite content from 10 to 60 wt. %, the coefficient of thermal conductivity increases by 1.5...6.0 times compared to the matrix material. A decrease in the temperature coefficient of linear expansion by almost 8 times is observed. At the same time, the decrease in specific heat capacity is about 20 %. If the graphite content is up to 20 wt. %, the matrix material practically does not increase hardness and density. The compressive strength of composites and its impact toughness decrease. A film was found on the surface of the metals, which in terms of properties is close to hard alloys. The film preserves the crystalline structure and creates friction conditions similar to the friction conditions of the graphite-graphite conjugation of materials. The wear resistance of the polymer composite filled with graphite is determined by the nature of the graphite, its dispersion, ash content, as well as the presence of abrasive impurities, the orientation of the graphite particles, and its content in the polymer matrix, etc.

Finally, the effect of thermally split graphite on phenylone was not investigated in [11]. As stated in the work, this problem is of scientific interest and needs to be solved. The results of tribological studies show that graphite-like materials increase the wear resistance by 1.3 times, and the friction coefficient decreases by 35...40 % compared to graphite plastic, which contains ordinary graphite. Systematic studies of changes in tribotechnical characteristics depending on the content of graphite plastic should have been conducted.

In work [12], it was found that under the mode of friction without lubrication, the maximum value of the performance criterion *pv* for graphite plastic was 22...25 MPa·m/s. At the same time, the optimal set of properties was demonstrated by a polymer composite with a graphite filler containing 15 wt. %. of thermally split graphite. The resulting composite has been extensively tested as a sliding bearing material for friction units of agricultural and transport equipment. In order to maintain high hardness and strength, along with the highest wear resistance, graphite-like materials are recommended to add graphite filler with a content of 5...30 % to phenylone. If the content of graphite in phenylone is more than 50 %, then despite the significant decrease in the coefficient of friction, there is a deterioration in the strength of the resulting polymer composite. However, it is not specified how the tribotechnical characteristics and tribological efficiency change.

Improvement of complex formation at the boundaries of separation and regulation of crystal transformation behavior of composites based on PA-6 with high mechanical and thermal properties are considered in work [13]. The influence of the glass fiber content on the crystalline transformation, thermal stability, thermal conductivity, and mechanical properties of PA-6 was studied and discussed. The results of temperature deviation, dynamic mechanical analysis, and thermal conductivity tests show a significant increase in the glass transition temperature and thermal conductivity of PA-6. The results of differential scanning calorimetry, Fourier transform infrared spectroscopy, and X-ray diffraction show that the transformation of PA-6 from $\gamma$ to $\alpha$ crystals is induced by interfacial complexation. The work offers a facile approach to produce materials with high thermal and mechanical properties that could potentially be used in automobiles, electronics, and related technologies. This indicates the need to study the set of tribotechnical characteristics and tribological efficiency.

In work [14] it was found that it is also advisable to use polyamide fiber of the arimide-T brand as a filler, which has high strength indicators. Compared to glass, carbon and basalt fibers, these organic fibers have good wettability with polymers. There is also a high strength of connection with the matrix, a lower tendency to crushing, high specific strength and stiffness. At that time, the tribological efficiency of such material was not investigated and the optimal filler content was not established.

In [15], the optimal concentration of silica in the polymer matrix was established (10 % by weight), when the "polymer composite-steel" conjugation of samples had a high level of tribological properties. The morphology of the steel surface before and after wear of the polymer composite was studied. It was found that the reduction of the coefficient of friction and the nature of wear are associated with the creation of an anti-friction coating on the surface of the steel. The influence of external factors (load, relative movement speed) on the friction and wear of the polymer composite (90 % Teflon+10 % silica) was revealed. It was established that such a polymer composite can work under the normal mode of friction under a load of up to 2.0 MPa and a speed of 1.25 m/s. Mathematical formulas describing the processes of friction and wear of the polymer composite were derived. It was established that the polymer composite with silica filler has a high level of physical, mechanical and thermophysical properties compared to the original polymer. The optimal concentration of silica in the polymer composite based on the dependence of tribotechnical characteristics requires justification.

In work [16] it is proposed to modernize the designs of mechanisms with the help of parts made of polymer composite materials. It is recommended to use polymer composite SSPA-6-30, which has high tribotechnical characteristics. The range of changes in tribotechnical characteristics and tribological efficiency of materials is not specified.

In [12], the dependence of the coefficient of friction and wear of a composite material based on phenylone C-2, containing thermally expanded graphite, on the load was revealed. Different modes of friction with and without lubrication are considered. It was determined that the minimum wear of the material during lubrication friction is achieved at a pressure of 5 MPa. It is shown that with an increase in the filler content from 5 to 25 wt. % coefficient of thermal conductivity increases by 4.0...40.8 % compared to unfilled phenylone. It was found that the introduction of thermally split graphite into phenylone in the amount of 5 wt. % leads to a decrease in heat capacity by 34 %, but the influence of filler content on tribotechnical characteristics was not investigated. For the tribological efficiency of composite materials, it was necessary to establish the dependence of tribotechnical characteristics on the filler content.

In [17], it was established that the optimal content of silica gel in the polymer matrix is 10 wt. %. The morphology of the steel friction surface after frictional interaction with a polymer composite based on aromatic polyamide and silica gel was studied. The formation of an anti-friction film on the friction steel surface was detected. This contributes to the reduction of the coefficient of friction, the temperature on the friction surface and the intensity of linear wear of the studied polymer composite. Physical-mechanical and thermal studies of the developed polymer composite were carried out and it was shown that the introduction of 10 wt. % of silica gel contributes to their increase by 5...10 %. It would be desirable to establish patterns of changes in the tribotechnical characteristics of the filler content.

In [18], the mechanisms of thermal destruction of both the basic polymer material and the one reinforced with carbon fibers were established. It was found that carbon fiber, regardless of its content in the composite material based on polytetrafluoroethylene, is mainly oriented perpendicular to the plane of application of forces. It is shown that with an increase in the carbon fiber content from 10 to 40 % by mass, the heat capacity decreases by 16...39 % compared to the matrix material. The optimal operating modes for the developed composite materials based on the *pv* criterion are substantiated: under the dry friction mode – up to 4 MPa·m/s; when rubbing with lubricant – up to 36.4 MPa·m/s. The dependence of the coefficient of friction on the modes of operation of the composite material based on polytetrafluoroethylene with a content of 20 wt. % of carbon fiber when lubricated with oil and water. In the study, there is no connection between tribotechnical characteristics and the criterion of workability of conjugations of samples and parts.

In [19] it was found that under the given conditions, the polymer composite material with a high-modulus PA-6.6+30 % F filler exhibits the best tribophysical characteristics compared to the PA-6.6 material. The proposed material when coupled with steel 1.1191 has a coefficient of friction 38...41 % lower and the temperature in the contact zone is 8...12 % lower than when coupled with material PA-6.6. At that time, composite materials require research into the regularity of changes in tribotechnical characteristics in various environments, as well as evaluation of tribotechnical efficiency.

Based on the literature, it can be asserted that composite materials based on phenylone C-1 and PA-6 polyamide with different filler content have high strength and positive values of tribotechnical characteristics. At the same time, the increased tribological efficiency of composite materials requires the study of patterns of change in wear intensity, friction coefficient, temperature in the contact zone depending on the filler content and specific load. It is necessary to establish the trends of changes in tribotechnical characteristics under friction conditions without lubrication and lubrication with water and I-50 oil. This makes it possible to control the level of wear resistance and reliability of tribological junctions of parts made of composite materials with high-modulus filler.

## 3. The aim and objectives of the study

The purpose of our study is to establish the patterns of changes in tribotechnical characteristics depending on the content of arimide-T and fullerene C-60 in the matrix materials phenylone C-1 and polyamide PA-6. This will make it possible to establish the tribological efficiency of the resulting composite materials.

To accomplish the set goal, the following tasks were solved in the work:

– to experimentally investigate changes in the tribotechnical characteristics of the composite samples depending on the content of the filler under conditions of friction without lubrication and to identify its optimal content;

– to experimentally investigate changes in the tribotechnical characteristics of composites under conditions of friction without lubrication depending on the criterion of performance of tribological junctions of the samples;

– to experimentally investigate changes in the wear and intensity of wear when lubricated with water and industrial oil I-50 of samples of composite materials based on phenylone C-1.

## 4. The study materials and methods

The object of our study is the process of changing the tribological efficiency according to the tribotechnical characteristics of composites based on phenylone C-1 and PA-6 polyamide with arimide-T filler and C60 fullerene.

The main hypothesis of the research assumes that the patterns of change in the tribotechnical characteristics of composites determine the change in their tribological efficiency.

An assumption was adopted: the reinforcing material of the filler is uniformly distributed in the matrix material of the composite.

Phenylone C-1 and polyamide PA-6 were taken as basic materials for the study of tribological efficiency and regularity of changes in tribotechnical characteristics of polymer composites, and arimide-T as a reinforcing substance.

Phenylone C-1 is a polymer material that belongs to the class of aromatic heat-resistant polyamides and is a linear heterochain polymer. Phenylone C-1 macromolecules consist of fragments of different structures connected by amide bonds. Phenylone C-1 is a pink powder with a bulk density of 0.2...0.4 g/cm$^3$.

The basic physical and mechanical properties of Phenylone C-1 are: density – 1350 kg/m$^3$; compressive yield strength – 220 MPa; impact strength – 20 kJ/m$^2$; Brinell hardness – 180 MPa; relative elongation – 5 %; heat resistance according to Vic – 563 K; thermal conductivity – 0.186...0.256 W/(m·K); water absorption in 24 hours is no more than 0.5 %.

Polyamide PA-6 belongs to the class of aliphatic polyamides and is a linear heterochain polymer. Polyamide PA-6 is a product of the polymerization of caprolactam. It has high physical and mechanical properties. Physical and mechanical properties of PA-6 polyamide: density – 1130 kg/m$^3$; heat resistance according to Vic – 463...473 K; destructive tensile stress – 55...77 MPa; in compression – 85...100 MPa, and in bending – 90...100 MPa; impact viscosity – 90...130 kJ/m$^2$; Brinell hardness – 100...120 MPa; coefficient of linear expansion – (8...10)·10$^6$ K$^{-1}$; thermal conductivity – 0.267...0.290 W/(m·K); water absorption – 10 %.

Arimide-T reinforcing fiber is a polyamide based on pyromellitic anhydride and 4.4-diamino-diphenyl ether. The fiber has an orange (orange, yellow-hot, red) natural color. The initial properties of the arimide-T fiber are: density – 1410...1430 kg/m$^3$; tensile modulus – 14.7 kN/mm$^2$; glass formation temperature – 653 K, during decomposition – 973 K, during operation – 573...623 K. Thermal aging: temperature – $T$=573 K; processing duration $\tau$=100 h; residual strength – $P$=80 %, at $T$=673 K, $\tau$=25 h – $P$=40 %.

Arimide-T fibers exhibit high adhesion to various binders. Having good mechanical properties, arimide-T also has high heat and temperature resistance and oxygen index. In addition to the above-mentioned properties, arimide-T withstands high-temperature thermal shock in the temperature range of 1073...1273 K and does not emit toxic products. Arimide-T fibers are resistant to microorganisms, chemical reagents, and various petroleum products.

Production of fullerenes is widely available for research owing to the method of evaporation of graphite in an electric arc. The method is the most effective for the synthesis of fullerenes, in particular C60 and C70, which are the main product of carbon vapor condensation – fullerene-containing carbon black. It is a promising additive that significantly improves lubricating properties. Compared to other carbon materials, pure fullerene and fullerene-containing carbon black significantly improve the antifriction and antiwear properties of steel-steel and steel-bronze tribological junctions, especially at high loads. The use of fullerene or fullerene-containing carbon black leads to the formation of a fullerene polymer film on the friction surface, which has a protective effect.

The technology for obtaining composites based on phenylone C-1 and polyamide PA-6 consists of the following processes: weighing components; mixing components; tableting of samples; drying and pressing of samples [20, 21]. The schematic sequence of the implementation of the acquisition processes is shown in Fig. 1.

Polyamide (PA-6 or phenylone C-1) from container 1 is fed by dosing device 3 for weighing on scales 4. The moisture content of the polyamide material is controlled by hygrometer 2. Arimide-T fibers are fed to cutting device 5. The length of the fiber is controlled by the adjuster of the device. After that, the chopped fiber enters container 6. Next, the fiber is fed in a given proportion to scales 8 by dosing device 7. The weighed matrix material and the filler (arimide-T and fullerene C60) enter electromagnetic apparatus 9, in which they are mixed. For better mixing of the specified mixture, we add ferromagnetic particles with parameters $\ell/d$=4…5.

Duration of mixing is 10…15 s. The electromagnetic induction of the magnetic field in the device is maintained within 0.10…0.12 T. The temperature in the apparatus varies between 293…298 K. Ferromagnetic particles are removed by magnetic separation after the mixing process is completed. Note that fullerene C60 is in a storage container and, with the help of dispenser 14, is also fed through scales 15 to the electromagnetic apparatus for mixing the components 9.

The finished mixture of composite components is fed to apparatus 10 for the preparation of samples. Samples of composites based on phenylone C-1 were formed under a pressure of 45 MPa, and on the basis of polyamide PA-6 – 40 MPa. After that, the samples were to be dried in chamber 11. The duration of drying is about 2…3 hours. Drying takes place to a moisture content of 0.1 % at a temperature of 383…398 K. The dried samples were fed into press apparatus 12.

The technology of pressing the samples of composites based on phenylone C-1 includes loading the samples into a heated mold to 528±3 K and holding without pressure for 10 minutes. at a temperature of 598±3 K. Holding under a pressure of 55 MPa for 5 min. is carried out at a temperature of T=598±3 K. Cooling of the samples is carried out under pressure to a temperature of 543±5 K, followed by pushing the sample out of the press mold.

The technology of pressing PA-6 polyamide composites includes loading the samples into a heated mold to a temperature of 453±3 K. Then, the procedure is carried out without pressure for 35 s at a temperature of 501±3 K. At that time, the process is carried out under a pressure of 45 MPa for 10 s and at a temperature of 501±3 K. Next, cooling is carried out under pressure to a temperature of 413±3 K and the sample is pushed out of the mold. On the basis of C-1 phenylone, the following groups of samples were prepared for tribological studies: without the content of arimide-T, and with the content of 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0 wt. % arimide-T+3 wt. % fullerene C60 powder.

Based on PA-6 polyamide, the following groups of samples were made for tribological studies: without arimide-T content and with 5, 10, 15, 20, 25, 30, 35, 40, 45 wt. % arimide-T+3 wt. % fullerene C60 powder.

The quality of the manufactured samples from composite materials was assessed by microstructure. The use of technologies for combining material compositions should enable a uniform distribution of arimide-T filler fibers in polymer matrices (Fig. 2).

One can also see the formation of monolithic structures of composites, which is possible when the fibers interact with the matrix. To this end, it is necessary to provide good wetting of the fibers by binders and high adhesion between the fibers and the matrix. This is characterized by the shear strength of the “fiber-matrix” contact.

A typical (Fig. 3, a) globular structure for amorphous polymers was established using electron microscopy. When reinforcing with arimide-T fibers (Fig. 3, b), the formation of a boundary layer is observed at the boundary of the separation of the filler and the binding material of the matrix. The structure of the polymer changes at the same time.

This technique of combining the components of the composite material is characteristic of preserving the fibrillar structure of the fibrous filler, which provides for high mechanical properties, including tribological ones.

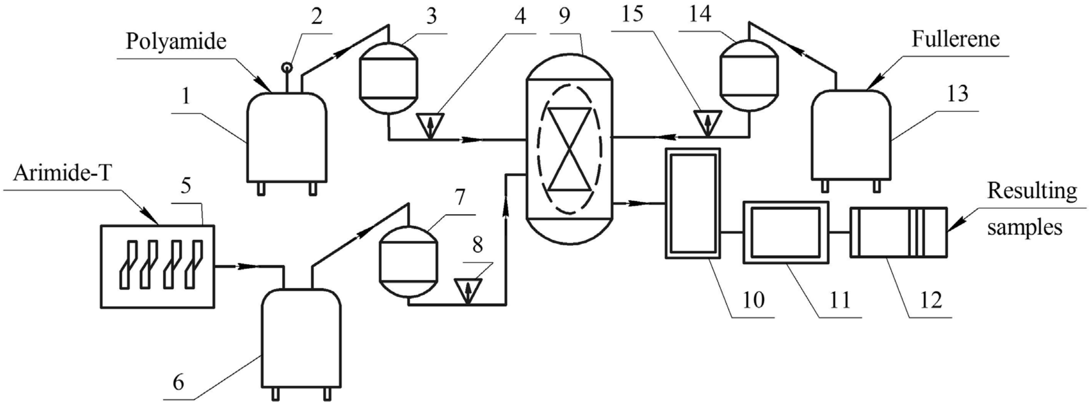


Fig. 1. Schematic of the technological process for obtaining samples of polymer composites: 1 — container for storage of polyamides; 2 — hygrometer; 3, 7 — dispenser; 4, 8 — scales; 5 — device for cutting fibers; 6 — container for storage of arimide-T fiber; 9 — electromagnetic device for mixing components; 10 — apparatus for tableting composites; 11 — drying chamber; 12 — press apparatus; 13 — container for fullerene storage; 14 — dispenser for supplying fullerene; 15 – scales

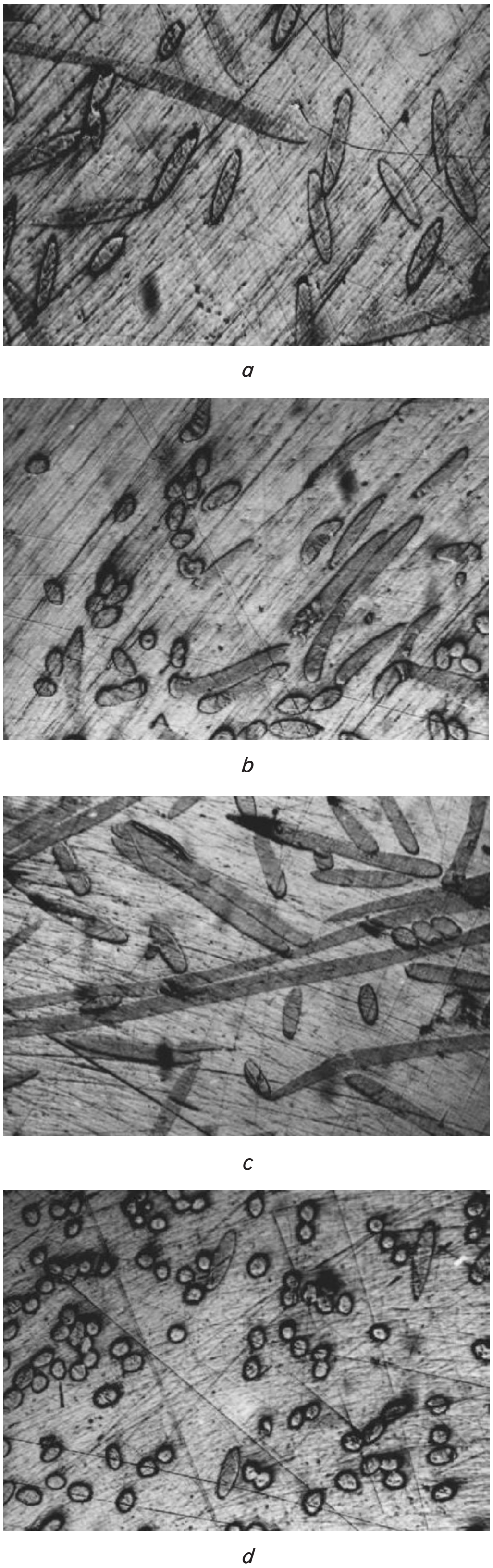


Fig. 2. Microstructure of samples of composites containing a matrix of phenylone C-1 and filler of arimide-T fibers+3 wt. % C60 fullerene powder: *a* — longitudinal section of a sample containing 10 wt. % of arimide-T fibers; *b* — longitudinal section of a sample containing 15 wt. % of arimide-T fibers; *c* — longitudinal section of a sample containing 20 wt. % of arimide-T fibers; *d* — cross section of a sample containing 15 wt. % of arimide-T fibers, x60

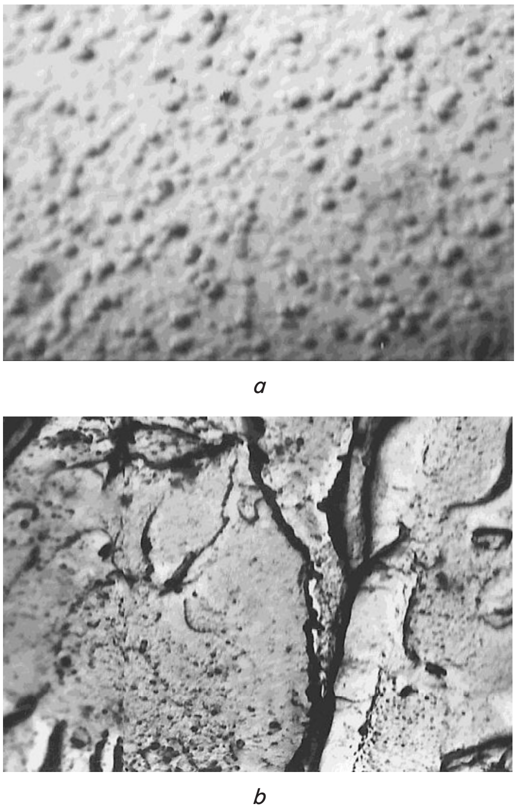


Fig. 3. Supramolecular structure of materials: *a* — phenylone C-1; *b* — composite based on phenylone C-1+15 wt. % arimide-T+3 wt. % of C60 fullerene powder, x10,000

Patterns of changes in tribotechnical characteristics and tribological efficiency were studied on samples of the obtained composites. The tests were carried out both under the mode of friction without lubrication and with oil and water lubrication. The following tribotechnical characteristics were studied: intensity of wear, coefficient of friction, and temperature in the friction zone.

Determination of the main characteristics of the wear process – the intensity of linear $I_h$ and mass $I_m$ wear – was carried out according to the formulas:

$$I_h = \frac{u_h}{L_{fr}}; \quad I_m = \frac{u_M}{\rho_u \cdot L_{fr} \cdot S_{ar}}, \tag{1}$$

where $u_h = \Delta h$ is the thickness of the worn layer, m; $u_M = \Delta M$ – amount of mass wear, kg; $L_{fr}$ – friction path, m; $S_{ar}$ – wear surface area, m$^2$; $\rho_u$ is the density of the studied sample, kg/m$^3$.

The coefficient of friction $f_{fr}$ was determined from the formula:

$$f_{fr} = \frac{M_{fr}}{p \cdot R \cdot S_{ar}}, \tag{2}$$

where $M_{fr}$ is the moment of friction, N·m; $p$ – specific load, Pa; $R$ is the radius of curvature of the friction surface, m; $S_{ar}$ is the contact area of the surface of the tribological coupling of samples.

The temperature in the contact zone of the tribological junction was recorded using a chromel-coppel thermocouple and a copper-constantan thermocouple and a PSMG-0.1 potentiometer. At the specified heating temperature of the friction surface, the thermocouple was pressed into the sample and connected to a loop oscilloscope with a MO17-150 galvanometer. Counting was carried out from the zero line of the oscilloscope, which corresponded to room temperature. Thermal curves were recorded at a belt speed of 0.01…0.25 m/s. They characterize the dependence of temperature on the duration of friction, which was monitored using a time relay.

Research into tribotechnical characteristics under the mode of friction without lubrication was carried out on the SMC-2 friction machine according to the "roller-roller" and "roller-pad" schemes. The friction path in the experiments was $L_{fr}$=1000 m, the specific load was 0.4…1.0 MPa, the sliding speed varied within 1.0…2.5 m/s. The wear of the samples was determined by the change in linear dimensions or mass by the weighing method on analytical balances VLR-200 with an accuracy of 0.0002 g.

Tests of the samples when lubricated with industrial oil I-50 and water were carried out on the MY-1M friction machine according to the "roller-pad" scheme at a speed of 1 m/s. It should be noted that the rollers are made of steel 45, heat-treated to a hardness of 45…48 HRC, and the pad is made of composite materials. The friction path when lubricated with water was 400 m, when lubricated with industrial oil I-50 – 3000 m. For comparative analysis, the coupling of the materials of the samples "bronze OTS-5-5-5-steel 45", "composite-steel 45" was studied. The pads are made of composite material and OTS-5-5-5 bronze, and the roller is steel 45.

Industrial oil I-50 is a general-purpose, distillatory oil. It is a base oil for selective cleaning without additives. The choice of industrial oil I-50 is due to the fact that the tested tribological junctions of the samples do not have special requirements for their antioxidative and anticorrosive properties.

The obtained data of experimental studies were subject to regression analysis.

The general form of regression equations with one variable is represented in the form of a polynomial of power *m*:

$$y(x)=\beta_1 x^m+\beta_2 x^{m-1}+\ldots+\beta_{n-1}x+\beta_n, \tag{3}$$

$\beta_1$, $\beta_2$,…,$\beta_n$ are unknown coefficients.

And the general form of regression equations with two variables is represented in the form of a polynomial of power *m*:

$$z(x,y)=\alpha_{11}x^2+\alpha_{22}y+2\alpha_{12}xy+$$
$$+\alpha_1 y+\alpha_2 x+\alpha_0, \tag{4}$$

where $\alpha_{11}$, $\alpha_{22}$, $\alpha_2$, $\alpha_1$, $\alpha_0$ are unknown coefficients.

Unknown coefficients were found by the method of least squares.

## 5. Results of research on the change in the tribological efficiency of composites according to the laws of change in their tribotechnical characteristics

### 5. 1. Results of experimental research into dependence of the tribotechnical characteristics of composites on the filler content during friction without lubrication

The results of our study on the influence of the content of the arimide-T filler in phenylone C-1 on the tribotechnical characteristics (intensity of linear wear, friction coefficient and temperature in the friction zone) under conditions of friction without lubrication are shown in Fig. 4. The conjugated sample is made of steel 45.

Statistical analysis of experimental data made it possible to construct the following regression equations:

$$I_h\times10^{-8}=0.0254c_m^2-0.7697c_m+6.2406,\ R^2=0.9989, \tag{5}$$

$$f_{fr}=0.0171c_m^2-0.4665c_m+6.8436,\ R^2=0.9981, \tag{6}$$

$$T=0.0029c_m^3-0.0718c_m^2+0.1233x+6.6091,$$
$$R^2=0.9635. \tag{7}$$

The results of tribological studies of samples of composites based on PA 6 with different contents of arimide-T filler and 3 wt. % of C60 fullerene powder, under conditions of friction without lubrication, are shown in Fig. 5. The conjugated sample is made of steel 45.

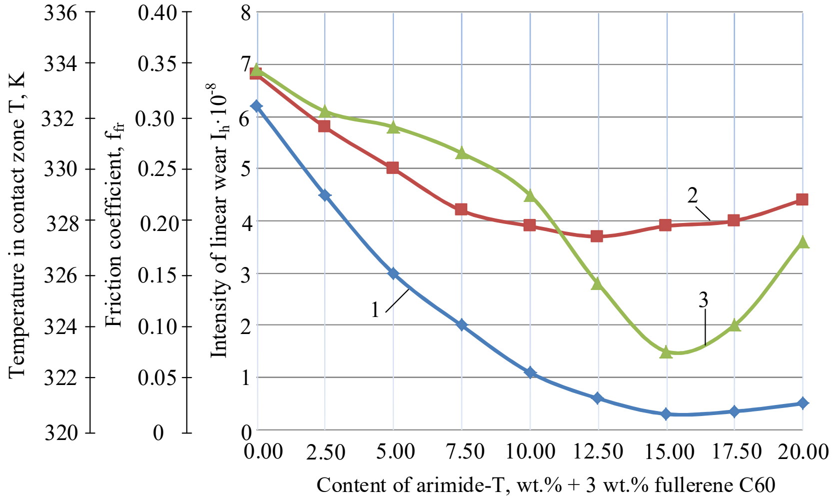


Fig. 4. Experimental dependences of tribotechnical characteristics of composites based on phenylone C-1+arimide-T+3 wt. % fullerene C60 on the content of arimide-T: 1 – intensity of linear wear; 2 – coefficient of friction; 3 – temperature in the contact zone, with the criterion of performance of the tribological junctions of the samples *pv*=1.0 MPa m/s, under conditions of friction without lubrication

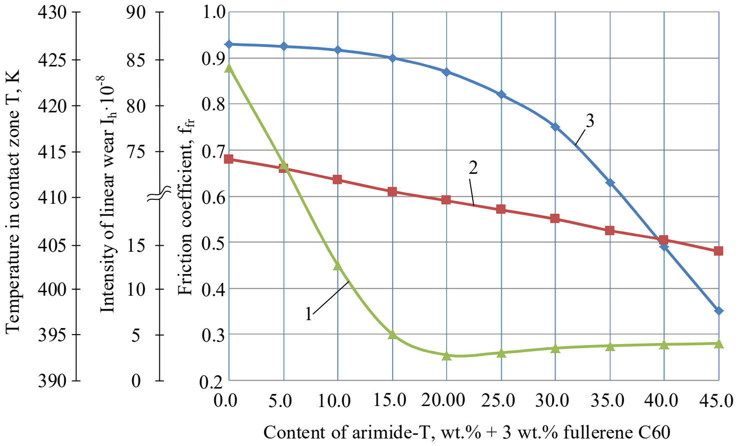


Fig. 5. Experimental dependences of wear intensity (curve 1), friction coefficient (curve 2), and temperature in the contact zone (curve 3) on the content of arimide-T+3 wt. % of C60 fullerene in PA-6 polyamide, at the performance criterion of tribological junctions of the samples $pv$=0.5 MPa m/s, under conditions of friction without lubrication

Statistical analysis of experimental data made it possible to construct the following regression equations:

$$I_h \times 10^{-8} = 0.0006c_m^2 - 0.0393c_m + 0.8389,\ R^2=0.9635, \quad (8)$$

$$f_{fr} = 0.0001c_m^2 - 0.0082c_m + 0.6945,\ R^2=0.9663, \quad (9)$$

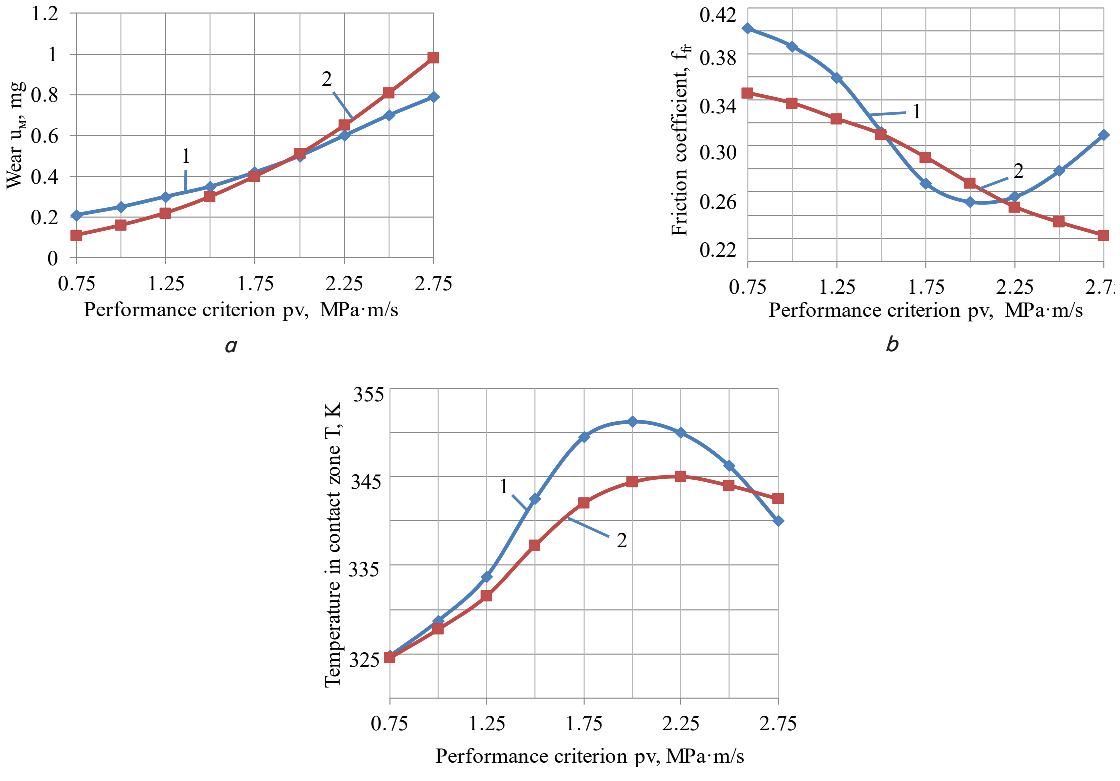
$$T = 0.00001c_m^3 - 0.0007c_m^2 + 0.0063c_m + 0.9226,$$

$$R^2=0.9826. \quad (10)$$

Knowing the resulting regularities, it is possible to establish the trend of changing the tribological efficiency of composites based on phenylone C-1 and polyamide PA-6 under conditions of friction without lubrication depending on the change in the content of the filler.

### 5. 2. Results of experimental dependences of tribotechnical characteristics of composites on the criterion of performance of tribological junctions of samples without lubrication

The results of comparative studies of the patterns of changes in tribotechnical characteristics of conjugated samples of composites from the performance criterion $pv$ are shown in Fig. 6. Composites were obtained on the basis of phenylone C-1 and polyamide PA-6, reinforced with arimide-T, and steel 45. The conjugated sample is made of steel 45.



*a*

*b*

*c*

Fig. 6. Experimental dependences of the performance criterion of samples: *a* — on the amount of wear; *b* — on the friction coefficient; *c* — on the temperature in contact zone of the composite: 1 — phenylone C-1+15 wt. % arimide-T+3 wt. % fullerene C60; 2 — polyamide PA-6 + 30 wt. % arimide-T+3 wt. % fullerene C60

Statistical analysis of experimental data made it possible to construct the following regression equations for the tribotechnical characteristics of phenylone C-1+15 wt. % arimide-T+3 wt. % fullerene C60 and polyamide PA-6+30 wt. % arimide-T+3 wt. % fullerene C60:

The regression equation of the amount of wear:

$$u_1=0.0797(pv)^2+0.0159(pv)+0.1529,\ R^2=0.9991, \quad (11)$$

$$u_2=0.1486(pv)^2-0.0867(pv)+0.0948,\ R^2=0.9999. \quad (12)$$

Friction coefficient regression equation:

$$f_{fr1}=0.3248(pv)^3-1.3403(pv)^2+1.1821(pv)+0.6494,$$

$$R^2=0.9813, \quad (13)$$

$$f_{fr2}=-0.0206(pv)^2-0.2245(pv)+0.8491,$$

$$R^2=0.9908. \quad (14)$$

Temperature regression equation in the contact zone:

$$T_1=-0.4288(pv)^3+1.617(pv)^2-0.9909(pv)+0.1744,$$

$$R^2=0.982, \quad (15)$$

$$T_2=-0.3196(pv)^2+1.5315(pv)-0.8622,$$

$$R^2=0.9707. \quad (16)$$

It can be seen that for the obtained patterns of tribotechnical characteristics from the performance criterion for composites based on phenylone C-1 and PA-6 polyamides for the optimal filler content, it is possible to use a comparative analysis of the tribological efficiency of these materials.

### 5. 3. Results of experimental research on the dependence of wear and wear intensity of composite samples lubricated with water and I-50 oil on specific pressure and filler content

The developed composites are planned to be used in tribological junctions of machine parts; as a rule, these coupled parts are made of OTS-5-5-5 bronze and steel 45 and work with oil lubrication. The study of the wear resistance of the samples of the created composites was carried out under similar conditions, that is, at friction with oil lubrication. Interaction with water is important for composites based on phenylone C-1. Research was also carried out when the couplings of the samples were lubricated with water.

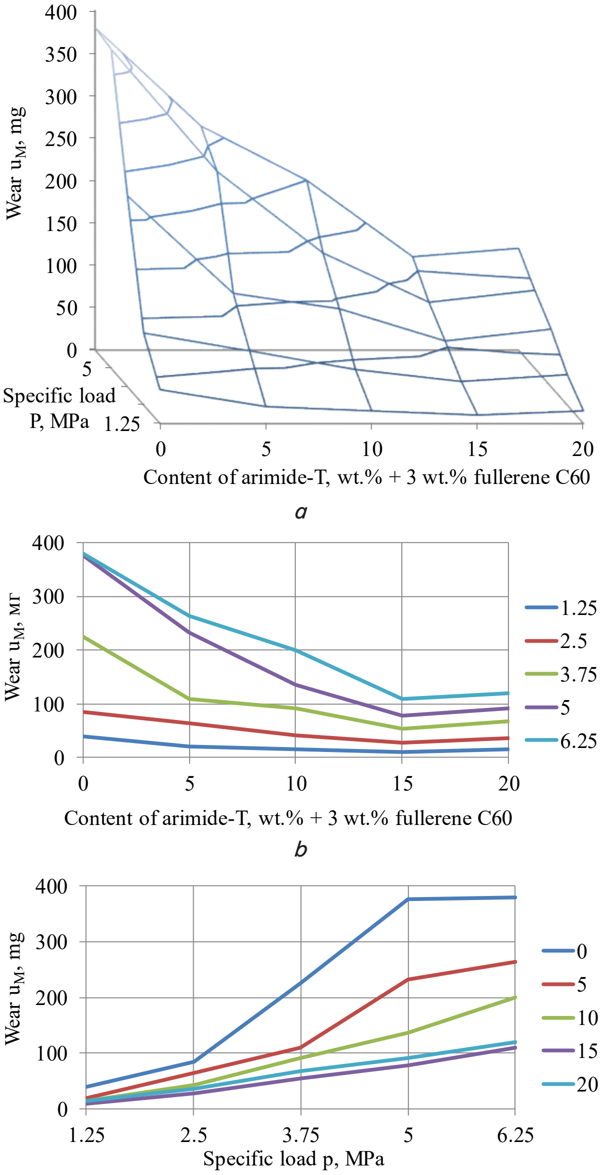
The results of the study of the conjugation of the samples under the conditions of wear of the tribological junctions of the samples lubricated with water and oil are shown in Fig. 7, 8.

The regression equation of wear under water lubrication conditions for the two variables $c_m$ and $p$ takes the form:

$$u(p,c)=17c_m^2-4.8571p^2-$$
$$-2363c_m p-139c_m+17.257p+320.2,\ R^2=0.9614. \quad (17)$$

The wear regression equation under conditions of lubrication with I-50 oil for the two variables $c_m$ and $p$ takes the form:

$$u(p,c)=0.2286c_m^2+0.2p^2+$$
$$+0.85c_m p-1.7114c_m-0.48p+0.7,\ R^2=0.9947. \quad (18)$$



*a*

*b*

*c*

Fig. 7. Experimental dependences of the wear of conjugated samples "composite-Steel 45", lubricated with water, with a matrix of composite – phenylone C-1: *a* – on the content of arimide-T filler and specific load; *b* – on the filler content at a constant specific load; *c* – on the specific load at a constant filler content

Our data on the patterns of change in wear of the "composite-steel 45" conjugation samples take into account the specific load, the content of arimide-T filler in the C-1 phenylone matrix, and the influence of water and I-50 oil. These factors will affect the tribological efficiency.

The results of the intensity of linear wear of the investigated composite materials based on phenylone C-1 and polyamide PA-6 are shown in Tables 1, 2. The tribological junctions of materials of the samples "composite-steel 45", "bronze OTS-5-5-5-Steel 45".

One can see that the intensity of linear wear of the resulting composites in the coupling "composite-steel 45" is compared with the intensity of wear of the coupling of "OTS bronze-5-5-5-Steel 45" samples. In this case, the content of the filler and the specific load, as well as the environment in which the conjugation of the samples work, vary.

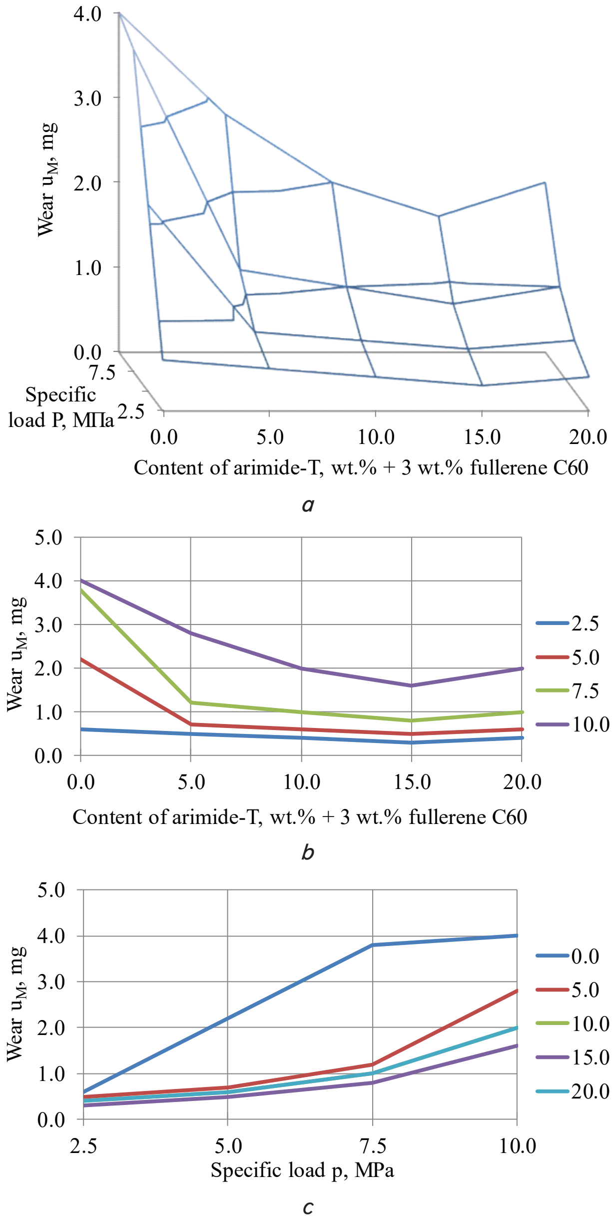


Fig. 8. Experimental dependences of the wear of conjugated samples "composite-Steel 45" lubricated with I-50 oil, with a matrix of composite – phenylone C-1: *a* – on the content of arimide-T filler and specific load; *b* – on the filler content at a constant specific load; *c* – on the specific load at a constant filler content

Table 1

Dependence of the intensity of linear wear of samples of composites based on phenylone C-1, reinforced with arimide filler-T+3 wt. % fullerene C60, and OTS-5-5-5 bronze, lubricated with water (*P*=5 MPa)

| Indicator | Phenylone S-1 | Composite based on phenylone C-1 with different content of arimide-T fibers, wt. %+3 wt. % fullerene C60 | | | | Bronze OCS 5-5-5 |
|---|---|---|---|---|---|---|
| | | 5 | 10 | 15 | 20 | |
| Linear wear intensity, μm/km | Intense wear | 322 | 186 | 98 | 112 | 122 |

Table 2

Influence of the specific load on the intensity of linear wear of composite materials based on phenylone C-1 and PA-6 polyamide and OTS-5-5-5 bronze in the medium of I-50 oil

| Material | Linear wear intensity (μm/km) at specific load, MPa | | | | |
|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 10 |
| Composite based on phenylone C-1+15 wt. % arimide-T+3 wt. % fullerene C60 | 0.62 | 1.58 | 2.34 | 2.98 | 3.20 |
| Composite based on polyamide PA-6+30 wt. % arimide-T+3 wt. % fullerene C60 | 1.24 | 6.38 | 14.50 | 23.62 | 25.80 |
| Bronze OCS-5-5-5 | 13.2 | 506 | Intense wear | | |

## 6. Discussion of results of the tribological efficiency of the studied composites

On can see (Fig. 4) that under identical conditions, composites based on phenylone C-1, reinforced with arimide-T with its content of 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0 wt. %+3% wt. % fullerene C60, have wear resistance 2.0...18.0 times higher than the matrix polymer. The coefficient of friction for composites decreases by 1.5...2.0 times, which is explained by the higher hardness of the composite. Based on the regression analysis of the database shown in Fig. 4, and regression equations (5) to (7), it was established that the composite based on phenylone C-1, reinforced with 15 wt. % arimide-T+3 % wt. % fullerene C60, possesses an optimal set of tribological properties and the best tribotechnical characteristics.

The resulting regression equations (8) to (10) based on the experimental data shown in Fig. 5 testify to the following. With an increase in the content of arimide-T from 5 to 45 wt. % in aliphatic polyamide PA-6, the wear resistance of the studied composites increases by an order of magnitude compared to the composite based on phenylone C-1 (Fig. 5, curve 1). While for the starting material PA-6 polyamide, the intensity of linear wear takes the value of $8.2 \cdot 10^{-7}$, for composites this indicator, with the increase in the amount of fibrous filler from 5 to 45 wt. %, decreases from $6.5 \cdot 10^{-8}$ to $2.7 \cdot 10^{-7}$. A decrease in the coefficient of friction is also observed: for a composite based on PA-6 polyamide, which contains 45 wt. % of arimide-T, the coefficient of friction is 1.75 times lower compared to PA-6 (Fig. 5, curve 2). The temperature that develops in the contact zone of the tribological junctions of the samples also decreases (Fig. 5, curve 3). In general, based on the results of our research, it can be concluded that the most optimal complex of tribological properties and tribotechnical characteristics is demonstrated by a composite containing 30 wt. % fiber arimide-T+3% wt. % fullerene C60 in PA-6 polyamide.

The wear mechanism for composites based on phenylone C-1 and polyamide PA-6 varies from adhesive to fatigue. When rubbing samples from the matrix materials of composites, their smearing on the surface of the conjugated metal sample is observed, and for the composite, the surface has a vitreous character [22]. Wear products formed in the tribological junctions of samples in the form of powder are removed from the friction zone.

Since the results of research on tribological properties and tribotechnical characteristics under the mode of friction without a lubricating medium of composites based on phenylone C-1, polyamide PA-6 with an arimide-T content of 15 and 30 wt.%, respectively, +3 % wt. % of C60 fullerene, are the best (Fig. 4), so it makes sense to give their comparative results based on the performance criterion *pv* of tribological junction.

Regression analysis of the experimental database to determine the regularities of changes in wear, friction coefficient, and temperature in the friction zone (Fig. 6), as well as the obtained regression equations (11) to (16), indicate the following. From the data shown in Fig. 6, *a*, the growth of the performance criterion (the product of the specific load by the speed of movement) slightly increases the wear of composite samples. The intensity of the increase in wear of the composite PA-6+30 wt. % arimide-T+3 % wt. % of fullerene C60 is greater than the composite of phenylone C-1+15 wt. % arimide-T+3 % wt. % fullerene C60. This can be explained by the fact that when the specific load changes, work of the friction forces and the time of the frictional connection of the "composite-metal" material conjugations increases. As the performance criterion increases, the friction coefficient (Fig. 6, *b*) for the studied composites decreases, but according to different patterns. For the PA-6 polyamide-based composite, this pattern is almost linear (Fig. 6, *b*, curve 2). For the composite based on phenylone C-1, the regularity (Fig. 6, *b*, curve 1) is complex: at first, the friction coefficient drops sharply, and at a certain value of the performance criterion, it begins to increase. This can be explained by the fact that for composites based on phenylone (Fig. 6, curve 1) and polyamide PA-6 (Fig. 6, curve 2) with different content of arimide-T, the actual contact area of the conjugated samples changes differently.

The decrease in the friction coefficient is also due to both a reduction in the time of "composite-steel" frictional contact and an increase in the tangential component of the sliding speed [23]. The specified circumstances contribute to the removal of wear particles from the friction zone of the conjugation of samples.

The contact temperature of the conjugates of samples from the C-1-based composite, 15 and 30 wt.%, respectively, arimide-T+3 wt. % of C60 fullerene in the friction zone reaches its maximum value ($T$=352 K) at $pv$=2 MPa·m/s (Fig. 6, *c*, curve-1). For a polyamide-based composite, the maximum temperature is 345 K (Fig. 6, *c*, curve 2), which is slightly reduced. This can be explained by the fact that when the product of specific load and speed changes, the work of friction forces and the time of frictional contact "polymer-steel" increases [24].

In the process of wear, the formation of finely dispersed wear products is observed, which fill micro-cavities on the surface of steel samples, while the friction is realized no longer on the steel but on the wear products. This indicates a pseudo-elastic abrasion mechanism, which provides the longest service life of couplings of samples and parts, minimal growth of gaps between them [25].

Regression analysis of experimental databases (Fig. 7, 8) and regression equations (17), (18) made it possible to obtain mass wear response surfaces of the composite based on phenylone C-1 on the mass content. % arimide-T and pressure. The results showed that the composite containing 15 wt. % arimide-T+3 % wt. % fullerene C60 demonstrates the least wear while lubricating in the medium of water (Fig. 7) and oil (Fig. 8), As can be seen from Fig. 8, the wear resistance of phenylone C-1 and composites based on it is significantly higher when lubricated with industrial I-50 oil.

This can be explained by the effect of water and oil at different temperatures in the friction zone on the molecular weight of phenylone. An increase in the water temperature in the friction zone leads to a decrease in the specific viscosity, which depends on the duration of contact of the composite with water [26].

An increase in the intensity of linear wear (Table 1, Fig. 7) of the studied composites lubricated with water was revealed. This can be explained by the destruction of the polymer matrix in the binder as a result of the influence of water and temperature [27], which develops during friction in the contact zone of the "polymer-metal" samples. It was found that the composite obtained on the basis of phenylone C-1+15 wt. % content of arimide-T+3% by mass. % of C60 fullerene has a 1.25 times lower intensity of wear compared to the wear of OCS 5-5-5 bronze. It should be noted that the material of the base of the phenylone C-1 composite itself has intensive wear.

Comparative tests on the tribological efficiency of sample couplings (Table 2) showed high wear resistance of the studied composites. The developed composites based on phenylone C-1 and polyamide PA-6, reinforced with arimide-T+3 wt. % of C60 fullerene, are not inferior to OTS-5-5-5 bronze in terms of wear resistance. When lubricated with oil and water, they significantly surpass it. At the same time, the wear of the conjugate sample when working with reinforced liners is approximately 3.5...4.5 times less than with bronze ones.

The obtained level of tribological efficiency and the regular nature of the tribotechnical characteristics of the studied composites indicate that we are dealing with new materials for structural purposes. These composites have high wear resistance and a low coefficient of friction. Based on their tribological efficiency, the resulting composites can be used in friction units of machines and mechanisms as antifriction materials that can work under various operating conditions [28]. The tribological efficiency of the studied composites correlates well with the maximum level of strength and reliability.

This study is characterized by the limitations of the arimide-T filler content in the matrix material of the composite. For phenylone C-1, the arimide content varies from 0 to 20 wt. %. For polyamide PA-6, the content of arimide-T varies from 0 to 45 wt. %. The ranges of variation of the filler are due to the expediency of a positive change in tribotechnical characteristics and a sufficient level of tribological efficiency of the conjugations of samples.

Adding C-60 fullerene powder as a filler is effective but this material is expensive. It is possible to eliminate this shortcoming by replacing this material with a cheaper analog. This requires additional research.

The development of our research may involve abrasive wear of the obtained composite materials. The study of composites for abrasive wear requires a special setup.

## 7. Conclusions

1. We have experimentally established regularities of changes in tribotechnical characteristics (wear intensi-

ty, friction coefficient, temperature in the contact zone of samples) of composites based on phenylone C-1 and polyamide PA-6 with a change in the content of arimide fibers-T+3 wt. % fullerene C60. It was found that with an increase in the content of arimide-T in composites based on phenylone C-1 and polyamide PA-6, the intensity of linear wear, the coefficient of friction, and the temperature in the friction zone decrease in different ways. This is observed at a predefined level of performance criterion. It was established that composites based on phenylone C-1 with an optimal arimide-T content of 15 wt.% +3 wt. % fullerene C60 have the best tribological efficiency, and those based on polyamide PA-6 30 wt. % arimide-T+3 wt. % fullerene C60.

2. For the conditions of dry friction of composites based on phenylone C-1 and polyamide PA-6, the comparative analysis established almost the same level of tribological efficiency. A similar pattern of changes in mass wear, friction coefficient, and temperature in the friction zone depending on the tribo-coupling performance criterion of the samples was revealed. The criterion for the performance of the conjugation of samples is equal to the product of the specific pressure and the speed of movement.

3. It was found that under conditions of lubrication with water, the wear of samples of composites based on phenylone C-1 is two orders of magnitude greater than wear under conditions of lubrication with industrial oil I-50. This can be explained by the destruction of the polymer component as a result of the influence of water and temperature. It has been experimentally proven that the developed composites with the best tribological efficiency in terms of wear resistance are 4 times higher than the wear resistance of OCS 5-5-5 bronze when lubricated with oil, while the wear intensity is 1.245 times lower.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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## Data availability

Data will be provided upon reasonable request.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work. Large Language Models were not applied in the course of the study and in the preparation of this work.

## References

1. Shelarea, S., Aglawea, K., Giria, S., Waghmare, S. (2023). Additive Manufacturing of Polymer Composites: Applications, Challenges and Opportunities. Indian Journal of Engineering and Materials Sciences, 30 (06). https://doi.org/10.56042/ijems.v30i6.4490
2. Neis, P. D., Ferreira, N. F., Poletto, J. C., Sukumaran, J., And , M., Zhang, Y. (2017). Tribological behavior of polyamide-6 plastics and their potential use in industrial applications. Wear, 376-377, 1391–1398. https://doi.org/10.1016/j.wear.2017.01.090
3. Kabat, O., Makarenko, D., Derkach, O., Muranov, Y. (2021). Determining the influence of the filler on the properties of structural thermal-resistant polymeric materials based on Phenylone C1. Eastern-European Journal of Enterprise Technologies, 5 (6 (113)), 24–29. https://doi.org/10.15587/1729-4061.2021.243100
4. Yeriomina, Y., Burya, A., Rybak, T. (2019). Investigating the influence of fine-dispersed aluminum, nickel and titanium on the properties of phenylone. Scientific Journal of the Ternopil National Technical University, 94 (2), 58–63. https://doi.org/10.33108/visnyk_tntu2019.02.058
5. Zhang, Y., Wang, M., Zhang, D., Wang, Y., Wang, L., Qiu, Y. et al. (2023). Crystallization and Performance of Polyamide Blends Comprising Polyamide 4, Polyamide 6, and Their Copolymers. Polymers, 15 (16), 3399. https://doi.org/10.3390/polym15163399
6. Srinath, G., Gnanamoorthy, R. (2007). Sliding wear performance of polyamide 6–clay nanocomposites in water. Composites Science and Technology, 67 (3-4), 399–405. https://doi.org/10.1016/j.compscitech.2006.09.004
7. Kabat, O., Sytar, V., Derkach, O., Sukhyy, K. (2021). Polymeric Composite Materials of Tribotechnical Purpose with a High Level of Physical, Mechanical and Thermal Properties. Chemistry & Chemical Technology, 15 (4), 543–550. https://doi.org/10.23939/chcht15.04.543
8. Tomina, A.-M. V., Burya, O. I., Lytvynova, Ye. E., Gavrish, V. M. (2020). The research on the influence of titanium-tantalum-tungsten-cobalt hard alloy on the tribological properties of phenylone C-2. Problems of Tribology, 25 (2), 42–48. https://doi.org/10.31891/2079-1372-2020-96-2-42-48
9. Liu, Y., Jiang, S., Yan, W., Qin, J., He, M., Qin, S., Yu, J. (2021). Enhanced mechanical and thermal properties of polyamide 6/p (N-(4-F-phenylmaleimide)–alt-styrene) composites based on interfacial complexation inducing crystal transformation. Polymer, 214, 123237. https://doi.org/10.1016/j.polymer.2020.123237
10. Makannavar, R., Keshavamurthy, R., Biradar, M. (2019). Mechanical Properties of Graphite Filled ABS Parts Developed by Fused Deposition Modelling. IOP Conference Series: Materials Science and Engineering, 577 (1), 012146. https://doi.org/10.1088/1757-899x/577/1/012146

11. Dudin, V., Makarenko, D., Derkach, O., Muranov, Y. (2022). Determining the influence of a filler on the properties of composite materials based on Phenylone C2 for tribojunctions in machines and assemblies. Eastern-European Journal of Enterprise Technologies, 5 (12 (119)), 38–46. https://doi.org/10.15587/1729-4061.2022.266160
12. Dudin, V., Makarenko, D., Derkach, O., Muranov, Y. (2021). Determination of the influence of a filler on the properties of composite materials based on polytetrafluorothylene for tribosystems of mechanisms and machines. Eastern-European Journal of Enterprise Technologies, 4 (12 (112)), 61–70. https://doi.org/10.15587/1729-4061.2021.238452
13. Korku, M., Feyzullahoğlu, E. (2024). Wear behaviour of glass fiber reinforced polyester composites under dry friction and fluid film lubrication. Materials Testing, 66 (5), 749–759. https://doi.org/10.1515/mt-2023-0420
14. Burya, A., Yeriomina, Y., Naberezhnaya, O., Arlamova, N. (2018). Thermal Resistance of Graphite Plastics Based on Aromatic Polyamide. American Journal of Analytical Chemistry, 09 (07), 331–339. https://doi.org/10.4236/ajac.2018.97026
15. Kabat, O. S., Derkach, O. D., Pavlushkina, N. V., Pikula, I. I. (2019). Polymeric composites of tribotechnical purpose based on fluoropolymers. Problems of Tribology, 92 (2), 75–81. https://doi.org/10.31891/2079-1372-2019-92-2-75-81
16. Aulin, V. V., Derkach, O. D., Makarenko, D. O., Hrynkiv, A. V., Krutous, D. I. (2020). Application of polymer composites in the design of agricultural machines for tillage. Problems of Tribology, 25 (2), 49–58. https://doi.org/10.31891/2079-1372-2020-96-2-49-58
17. Jiang, S., Cheng, L., Yuan, H., Li, X. (2024). Highlight Removal Emphasizing Detail Restoration. Applied Sciences, 14 (6), 2469. https://doi.org/10.3390/app14062469
18. Żywica, G., Bagiński, P., Roemer, J., Zdziebko, P., Martowicz, A., Kaczmarczyk, T. Z. (2022). Experimental Characterization of a Foil Journal Bearing Structure with an Anti-Friction Polymer Coating. Coatings, 12 (9), 1252. https://doi.org/10.3390/coatings12091252
19. Kobets, A., Aulin, V., Derkach, O., Makarenko, D., Hrynkiv, A., Krutous, D., Muranov, E. (2020). Design of mated parts using polymeric materials with enhanced tribotechnical characteristics. Eastern-European Journal of Enterprise Technologies, 5 (12 (107)), 49–57. https://doi.org/10.15587/1729-4061.2020.214547
20. Lyashuk, O., Sokil, B., Hevko, R., Aulin, V., Serilko, L., Vovk, Y. et al. (2021). The dynamics of the working body of the tubular conveyor with the chain drive. Journal of Applied and Computational Mechanics, 7 (3), 1710–1718. https://doi.org/10.22055/JACM.2021.35725.2719
21. Nazarenko, I., Mishchuk, Y., Mishchuk, D., Ruchynskyi, M., Rogovskii, I., Mikhailova, L. et al. (2021). Determiantion of energy characteristics of material destruction in the crushing chamber of the vibration crusher. Eastern-European Journal of Enterprise Technologies, 4 (7 (112)), 41–49. https://doi.org/10.15587/1729-4061.2021.239292
22. Kušter, M., Samardžija, Z., Komelj, M., Huskić, M., Bek, M., Pierson, G. et al. (2024). Effect of Al-Cu-Fe Quasicrystal Particles on the Reinforcement of a Polymer–Matrix Composite: From Surface to Mechanical Properties. Crystals, 14 (3), 216. https://doi.org/10.3390/cryst14030216
23. Nuruzzaman, D. M., Chowdhury, M. A., Rahman, Md. M., Kowser, Md. A., Roy, B. K. (2015). Experimental Investigation on Friction Coefficient of Composite Materials Sliding Against SS 201 and SS 301 Counterfaces. Procedia Engineering, 105, 858–864. https://doi.org/10.1016/j.proeng.2015.05.106
24. Jean-Fulcrand, A., Masen, M. A., Bremner, T., Wong, J. S. S. (2017). High temperature tribological properties of polybenzimidazole (PBI). Polymer, 128, 159–168. https://doi.org/10.1016/j.polymer.2017.09.026
25. Suffo, M., Pérez-Muñoz, C., Alba, G., Villar, M. P. (2024). An Innovative Polypropylene/Waste Cork Composite Material for Spirit and Wine Stopper Caps. Applied Sciences, 14 (7), 3014. https://doi.org/10.3390/app14073014
26. Røn, T., Lee, S. (2014). Influence of Temperature on the Frictional Properties of Water-Lubricated Surfaces. Lubricants, 2 (4), 177–192. https://doi.org/10.3390/lubricants2040177
27. Musthaq, M. Ahmed., Dhakal, H. N., Zhang, Z., Barouni, A., Zahari, R. (2023). The Effect of Various Environmental Conditions on the Impact Damage Behaviour of Natural-Fibre-Reinforced Composites (NFRCs)—A Critical Review. Polymers, 15 (5), 1229. https://doi.org/10.3390/polym15051229
28. Roszak, M. R., Kurzawa, A., Roik, T., Gavrysh, O., Vitsiuk, I., Barsan, N. et al. (2023). Friction films analysis and tribological properties of composite antifriction self-lubricating material based on nickel alloy. Materials Science-Poland, 41 (3), 1–17. https://doi.org/10.2478/msp-2023-0031