The introduction of polymer-composite materials makes it possible not only to solve the problem of increasing durability, reducing the mass and cost of machines, but also, by introducing fillers, to adapt them to the required operating conditions. At the same time, there is a problem regarding the high cost of technologies for obtaining composites, which limits their widespread implementation. That is why the object of this research is the processes of influence of the filler on the characteristics and properties of polymer-composite materials.

Complex laboratory studies of physical and mechanical characteristics, tribological and thermophysical properties of the developed polymer-composite materials based on Phenylone C2 were carried out. The dependence of the coefficient of friction and wear of the material based on Phenylone C2, containing thermally expanded graphite, on the pressure and nature of counter-bodies during friction with lubrication and without it was established. It was revealed that the minimum amount of wear of the material, with friction with lubrication, is achieved under the pressure on tribojunction of 5 MPa. It was established that with an increase in the concentration of filler from 5 to 25 wt% the coefficient of thermal conductivity increases by 4–40.8 %, compared with that non-filled with Phenylone C2. It was found that the introduction of thermally expanded graphite into Phenylone C2 in the amount of 5 wt % leads to a decrease in heat capacity by 34 %. The proposed technology of obtaining polymer-composite materials in the electromagnetic field provides sufficient physical and mechanical characteristics, tribological properties and low cost of finished products (parts).

The results reported here make it possible to adapt the physical and mechanical characteristics, thermophysical and tribological properties of polymer-composite materials to certain modes of operation of movable junctions

Keywords: Phenylone C2, thermally expanded graphite, electromagnetic field, microstructure of materials, thermal conductivity percolation

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DETERMINING THE INFLUENCE OF A FILLER ON THE PROPERTIES OF COMPOSITE MATERIALS BASED ON PHENYLONE C2 FOR TRIBOJUNCTIONS IN MACHINES AND ASSEMBLIES

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1. Introduction

The widespread introduction of composite materials of various origins in modern mechanical engineering is justified by the simplicity of adapting their characteristics and properties to the required working conditions. The lion's share of tribojunction parts is made of metals and their alloys. This is due to the operation of most movable connections under conditions of high temperatures, significant linear speeds, and alternating loads. At the same time, the cost of manufacturing such movable connections and their reliability are not always comparable. One of the promising ways to solve this problem is to design polymer-composite materials (PCM) for structural purposes [1]. This is primarily due to their high reliability, ability to work under a friction mode with lubrication, and resistance to a significant amount of aggressive chemicals. In addition to advantages, PCM have a number of disadvantages, namely, limited operating modes (magnitude and nature of the load, linear sliding speed) and technological modes of processing the source material into articles [2, 3]. The main direction of improving the characteristics of PCM is the introduction of special fillers in their structure, but often, due to the high cost of the materials obtained, their widespread use is limited. That is why designing new or improving existing technologies for making PCM at low cost is an urgent task of materials science and mechanical engineering. The study of the characteristics and properties of the PCM is the basis for designing materials with programmed properties, which will improve the existing structures of movable connections in machines and mechanisms.

2. Literature review and problem statement

The introduction of PCM in the tribojunctions of machines and mechanisms makes it possible to increase their durability, and, if necessary, to achieve the desired (programmed) resource. At the same time, depending on the operating modes of movable connections, different PCM are used in their structures, both in terms of cost and characteristics. The main direction of improving the characteristics and properties of these materials is the introduction of fillers into their structure. This makes it possible to adapt them to work under certain modes of operation. One of the common PCM for structural purposes are polyamides. Aliphatic polyamides, in comparison with aromatic polyamides, have a lower cost and a simpler technology of processing into articles [3] while the scope of their application is limited to a narrow range of operating modes [4]. Work [4] reports the results of studies of the characteristics and properties of aliphatic polyamides filled with high-modulus fillers. However, the studies were carried out at insignificant pressure value of 0.5 MPa and a linear sliding speed of 0.785 m/s. This imposes certain restrictions on friction units in which the performance of the specified PCM will be ensured. In addition, most of the materials given in [4] have a high coefficient of friction and the amount of wear. An option to overcome the relevant limitations is the introduction of low-cost fillers, such as graphite of various shapes and fibrous fillers, into the composition of PCM [5]. Graphite in the structure of the material makes it possible to reduce the coefficient of friction, and as a result, the temperature in the friction vicinity. This contributes to an increase in the factor *pv* – up to 5 MPa·m/s. The introduction of graphite into PCM leads to a decrease in physical and mechanical characteristics, such as toughness and elastic limit during compression, which can further lead to the destruction of parts due to insufficient strength. One of the options for expanding the range of operating modes of parts made of aliphatic polyamides is the introduction of nanomaterials into their structure [6]. The study proved the possibility of a significant increase in load and sliding speed at created material friction. However, the high cost of fillers and the significant complexity of the technological process of obtaining PCM significantly increases its cost.

An option to overcome the corresponding difficulties may be the use of aromatic polyamide C2. Its characteristics and properties significantly exceed those compared to aliphatic polyamide. The main disadvantage of aromatic polyamide C2 is the relatively high coefficient of friction at friction without lubrication. To this end, friction modifiers are introduced into its structure. In [7], to reduce the coefficient of friction and the amount of wear, it is proposed to add technical carbon to the matrix. It was established that the filling of the matrix with 15 wt% of technical carbon can significantly reduce the coefficient of friction and the intensity of linear wear. However, the study was carried out at a relatively narrow range of friction modes, namely at a pressure value of 0.5–1.5 MPa and a linear slip speed of 0.75–1.25 m/s, which limits the scope of such materials. It is possible to solve this problem by introducing inexpensive fillers with better tribological properties, for example, thermally expanded graphite (TEG). This approach is used in work [8]. The study confirmed the positive effect of the introduction of the specified filler into Phenylone C2 and the tribological indicators of PCM. However, the cited work does not pay attention to the issue of the influence of fillers of different brands on the physical and mechanical characteristics of the resulting materials, which complicates the recommendations for their use in specific friction units. A variant to overcome the corresponding difficulties may be the introduction of dispersed fillers (metal powders, titanium, etc.) into the structure of Phenylone C2. This approach is used in [9]. The above results show that the introduction of the proposed filler, titanium-tantalum-tungsten-cobalt alloy, reduces the abrasion index and the intensity of linear wear by 20 % and 35 %, respectively. The work also confirmed a slight increase in the physical and mechanical characteristics of the designed materials. Studies have established that the optimal content of the filler is 3 wt%. The high cost of the filler and the need for uniform distribution of a small volume of filler in the matrix complicates the technological process of obtaining finished articles (parts).

An option to overcome difficulties in reducing the coefficient of friction and ensuring the necessary physical and mechanical characteristics may be to design oil-filled PCM. This approach is used in [10]. Studies have found that the introduction of an absorbingly modified mineral nanofiller and lubricant into the composition of Phenylone C2 leads to a decrease in the coefficient of friction in a wide range. However, the paper states that in order to obtain the filler, preliminary purification and dispersion of its particles to a nanodispersed state was carried out, followed by acid modification of minerals. These technological operations require special equipment and significantly increase the cost of PCM, which limits the scope of their application.

One of the options to overcome the corresponding difficulties may be to use several fillers. Work [11] reports the results of studies into the characteristics and properties of Phenylone C2 filled with several fillers. It was shown that the addition of nanofillers leads not only to an increase in some characteristics of the obtained PCM but also to a decrease in the tribological properties of the resulting materials. Therefore, the introduction of fluoroplastic in the structure of Phenylone C2 is proposed, in addition to nanoscale fillers. Nevertheless, the introduction of three fillers into the matrix requires their quality distribution in the structure and, as a result, leads to an increase in the complexity of technological processes for treating such PCM. In the work, studies have been carried out under the condition of friction of the designed materials without lubrication on the counter-body from steel only. In addition, issues related to the effect of the filler on the impact of the PCM toughness, thermophysical properties, and tribological properties under the condition of friction with lubrication, including for various materials, remained unresolved.

Based on the above review, there is reason to believe that studies on the development of PCM based on aromatic polyamide, which has sufficient physical and mechanical characteristics, tribological properties, and low cost of finished articles, are promising.

3. The aim and objectives of the study

The aim of this study is to determine the effect of the filler on the characteristics and properties of polymeric composite materials obtained using a simple technology of their processing. This will make it possible to justify the feasibility of using parts from the designed PCM in mechanisms and machines under different operating conditions.

To accomplish the aim, the following tasks have been set:

– to analyze the microstructure of the designed PCM, justify the features of the distribution of the filler in the matrix;

– to investigate the physical, mechanical, thermophysical characteristics and tribological properties of the designed PCM, based on Phenylone C2 and TEG.

4. The study materials and methods

The object of our research is the processes of influence of the filler on the characteristics and properties of polymer-composite materials.

The studies were carried out on samples of PCM, made on the basis of Phenylone C2, and a filler – TEG. The aromatic polyamide Phenylone C2 is a product of polycondensation of aromatic diamine and chloroanhydride of isophthalic acid. This polymer is chemically resistant, it has high strength and wear resistance, can work for a long time at a working area temperature of up to 200 °C. TEG is obtained by multistage chemical-thermal processing of crystalline graphite. This work uses TEG obtained by processing graphite of grades B and HL-2. The main difference between these brands of original graphite is their origin. Graphite of grade B is obtained artificially, by heat treatment of finely crushed coke and carbon binder – pitch. Graphite of brand HL-2 is of natural origin. Counter-bodies are discs from steel 45 (1.1191, EN 10083) and copper (EN 13602:2002, IDT). The technology of preparation of PCM components involved drying: TEG at a temperature of 200 °C for 2 hours, Phenylone C2 at a temperature of 200–240 °C for 1.5 hours. Mixing of PCM components was performed in a dry state, at the ABC-150K installation, for 60...80 seconds in a rotational electromagnetic field with a magnetic induction value of 0.09...0.14 tesla using ferromagnetic elements. The removal of the latter from PCM was performed by magnetic separation. The resulting composition was processed into samples by direct compression pressing.

We determined the heat capacity and thermal conductivity in accordance with GOST 15173-70 on the device ITEM-1M. The arithmetic average value obtained as a result of at least 10 measurements, which differed by no more than 1 %, was taken as the ultimate result. Thermostating of the studied samples at different temperatures is provided by the ITEM-1M device.

The study of friction surfaces and the distribution of TEG in the polymer matrix was carried out using the microscope NEOFOT 30 (Germany) (Fig. 1) [12].

Fig. 1. Optical microscope NEOFOT 30: 1 – screen for visual analysis; 2 – screen for taking pictures

The coefficient of friction was determined on the friction and wear machine SMC-2 according to the procedure given in [4].

The coefficient of sliding friction was determined by the formula:

$$f = \frac{M_{kp}}{P \cdot \Delta}, \tag{1}$$

where M_{kp} is the torque arising on the disk, N·m; P – sample load, N; Δ – paper step, m. For all experiments, the same: Δ=0.0025 m.

The pressure on the tribojunction was changed in the range from 1 MPa to 15 MPa.

The temperature in the friction zone was determined using the Termometer 301 Type K chromel-alumel electron thermocouple (China). The hole for measuring temperature was made to a depth equal to half the diameter of the sample, and at a distance of 1 mm from the friction surface.

The strength properties of PCM were determined on the FP-100 test machine (Germany), according to GOST 4651-82. For the study, we used samples with a diameter of 10 and a height of 15 mm.

The magnitude of the fracture stress during compression (Σ_p) was calculated by the formula:

$$\Sigma_p = p / A, \tag{2}$$

where P is the pressure, MPa.

A – minimum cross-sectional area of the sample, mm^2;

$$A = \pi d^2 / 4, \tag{3}$$

where d is the diameter of the sample, mm.

The relative deformation at compression (ε) was calculated by the formula:

$$\varepsilon = \Delta h_p \cdot 100 / h_0, \tag{4}$$

where Δh_p is the magnitude of the decrease in the height of the sample, mm;

h_0 – initial sample height, mm.

The impact strength was determined on the pendulum copra KM-0.4 according to the Sharpie method in line with GOST 4647-80 at a temperature of 23±2 °C and a relative humidity of 50±5 %.

The impact strength of samples from PCM was calculated by the formula:

$$a_n = \frac{J_n}{b \cdot s \cdot 1000}, \tag{5}$$

where J_p is the impact energy spent on the destruction of the sample, kJ/(kg·cm^2), registered on the digital display of the device;

b – sample width in its middle, mm;

s – thickness of the sample in its middle, mm.

5. Results of research on the characteristics and properties of polymer-composite materials

5. 1. Analysis of the microstructure of composite materials

The study of the microstructure of the resulting PCM based on Phenylone C2 (Fig. 2) has made it possible to establish that TEG, regardless of its content in the material, is mainly oriented perpendicular to the direction of pressing.

Analysis of micro photographs of surfaces (Fig. 2) indicates a satisfactory distribution of the filler in the matrix, regardless of its quantity (volume).

Analysis of photographs in the intersections of parallel directions of application of force shows that the filler in them has local clusters (Fig. 3, *b*, *c*). It was established that with an increase in the content of TEG to 15 and 25 wt% there is a delamination of the structure of PCM in the plane of the parallel direction of pressing during the processing of the material (Fig. 3).

In addition, the analysis of photos (Fig. 4) taken with a magnification of ×300 shows that the filler in the finished PCM has a branched and gnarled structure.

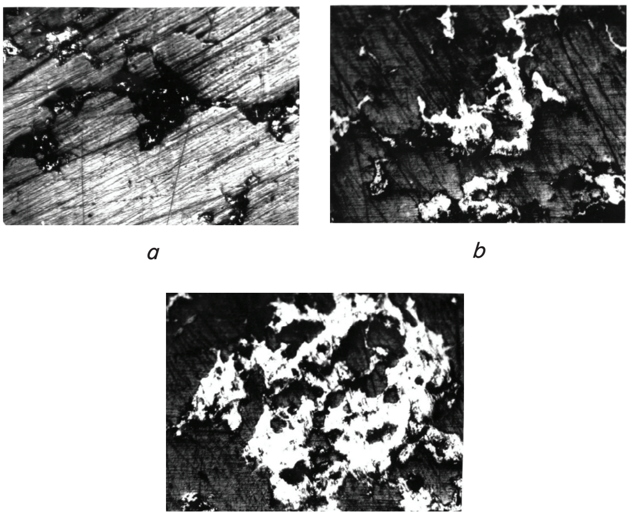

Fig. 2. Microstructure in sections perpendicular to the direction of pressing polymer-composite materials based on Phenylone C2 filled with thermally expanded graphite: *a* – 5 wt%; *b* – 15 wt%; *c* – 25 wt%; ×150

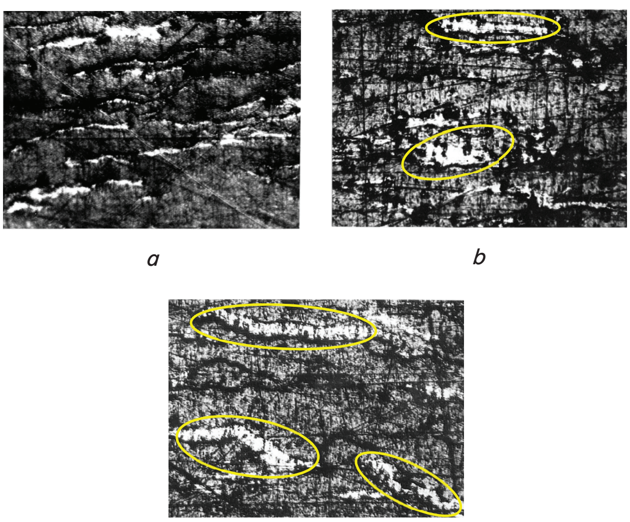

Fig. 3. Microstructure in sections of parallel direction of pressing polymer-composite materials based on Phenylone C2 filled with thermally expanded graphite: *a* – 5 wt%; *b* – 15 wt%; *c* – 25 wt%; ×150

Analysis of the photo (Fig. 4, *a*) shows that the filler, at a concentration of 15 wt%, is distributed in the matrix satisfactorily. At the same time, in Fig. 4, *b* (filling 25 wt%) there is an uneven distribution of the filler with the present local places of its insignificant concentration (highlighted zones) and zones with a significant accumulation of TEG.

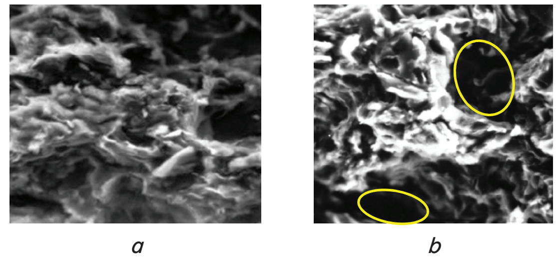

Fig. 4. Microstructure of polymer-composite materials based on Phenylone C2, filled with thermally expanded graphite: *a* – 15 wt%; *b* – 25 wt%; ×300

5. 2. Results of studying the physical, mechanical, thermophysical characteristics and tribological properties of the designed composite materials

The results of determining the effect of the filler on the magnitude of the destruction stress and the modulus of elasticity during compression of PCM are shown in Fig. 5.

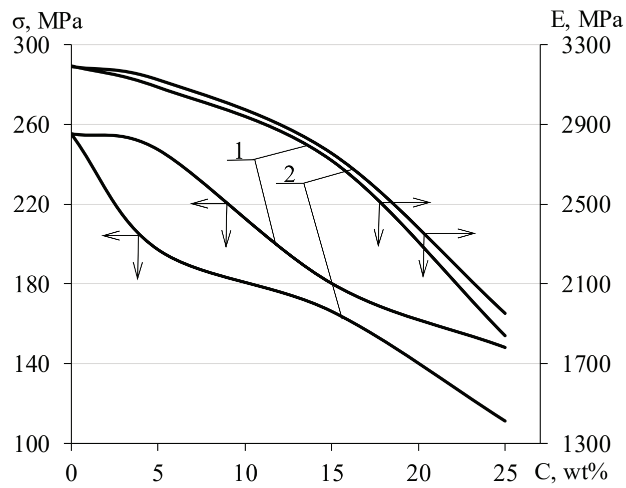

Fig. 5. Dependence of the magnitude of the fracture stress and the modulus of elasticity during compression of polymer-composite materials based on Phenylone C2 on the content (wt%) of thermally expanded graphite of grades: 1 – HL-2; 2 – B

The concentration of filler in PCM in the amount of 5 wt % leads to a slight decrease in the modulus of elasticity during compression, regardless of its chosen type. At the same time, the magnitude of the intensity of destruction during compression, subject to the introduction of 5 wt% TEG HL-2, decreases slightly, by 3.1 % only. When using TEG B, there is a sharp decrease in this indicator – by 22.7 %. Introducing 15 wt% of TEG HL-2 leads to a decrease in this indicator, compared to that with unfilled material, by 29.4 % (from 255 MPa to 180 MPa). A further increase in the concentration of filler up to 25 wt % leads to a significant decrease in both the magnitude of the fracture stress and the modulus of elasticity during compression, regardless of its brand.

Our results (Fig. 6) indicate that the introduction of 5 wt% TEG leads to a sharp decrease in the impact strength of PCM, by 67.8 % and 72.4 %, respectively, for fillers HL-2 and B. Subject to the introduction of 25 wt% of the filler, regardless of its brand, the impact toughness becomes so insignificant (less than 7.5 kJ/m^2) that it becomes an obstacle to the use of such PCM as structural ones.

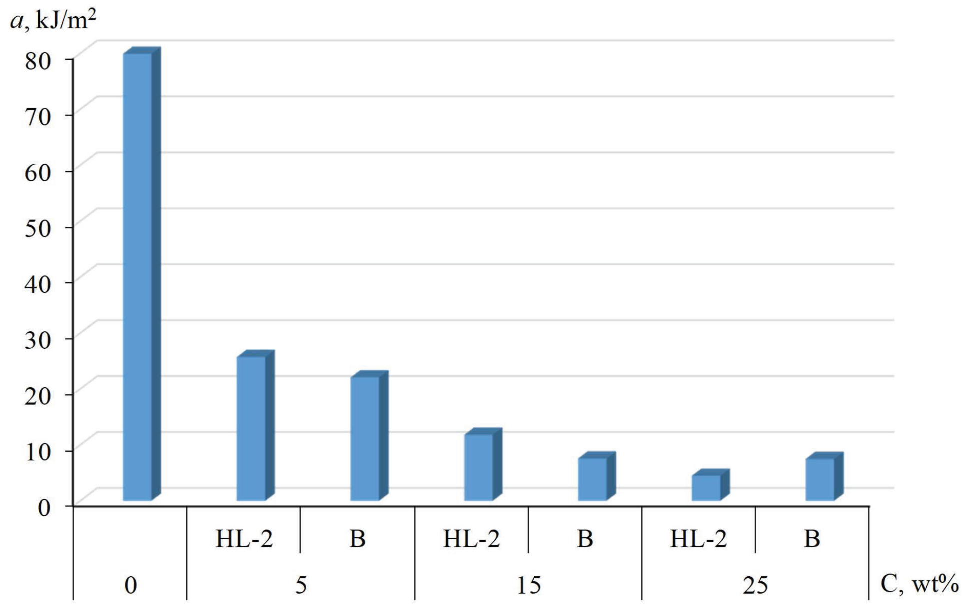

Fig. 6. Dependence of the impact strength of Phenylone C2 (without filling) and polymer-composite materials based on it on the content (wt%) of thermally expanded graphite of grades HL-2 and B

Based on our results (Fig. 5, 6), the optimal value of the concentration of the TEG filler in the Phenylone C2 matrix should be in the range from 5 to 15 wt%. This content of the filler makes it possible to obtain PCM having sufficient physical and mechanical characteristics for their use as structural materials.

The stress-deformation curve for Phenylone C2 without fillers (Fig. 7, curve 1, shown partially, without a section after the fluidity site) is characteristic of polymeric materials. In the case of the introduction of TEG in the amount of 5 wt%, curves σ–ε (Fig. 7, curves 2) have a similar shape to that unfilled with Phenylone C2. When filling TEG with 15 and 25 wt% of Phenylone C2, there is a dramatic change in the dependence of stress and deformation. The deformation during the destruction of the sample is more than twice less, both in comparison with that unfilled with Phenylone C2, and subject to filling by 5 wt%.

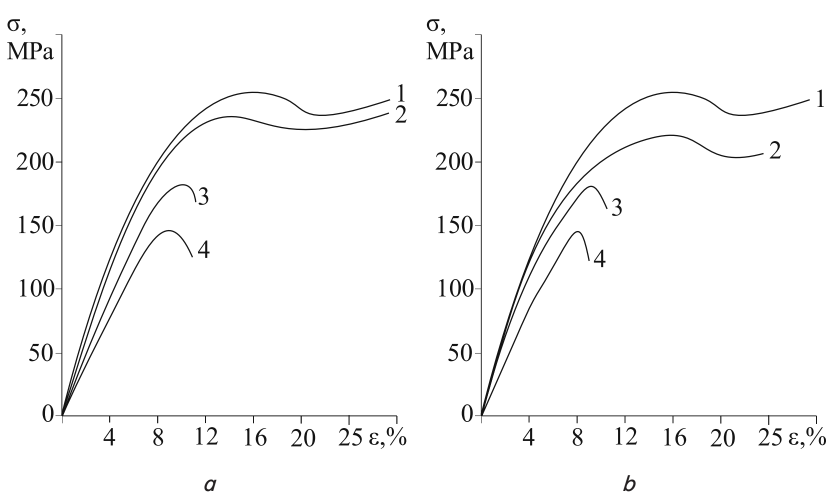

Fig. 7. Curves σ–ε of Phenylone C2 and polymer-composite materials based on it: *a* – filler HL-2; *b* – filler B; 1 – Phenylone C2; 2 – Phenylone C2+5 wt % thermally expanded graphite; 3 – Phenylone C2+15 wt % thermally expanded graphite ; 4 – Phenylone C2+25 wt % thermally expanded graphite

In general, the introduction of TEG into the structure of Phenylone C2 leads to a decrease in all the physical and mechanical characteristics of the resulting PCM. Nevertheless, even under the condition of a filler concentration of 15 wt%, the strength indicators of PCM have a sufficient level for the use of such materials as structural ones in the tribojunctions of mechanisms and machines.

The results of studies of the influence of TEG and temperature on the specific heat capacity and the coefficient of thermal conductivity of PCM, based on Phenylone C2, are shown in Fig. 8. It was established that the heat capacity of Phenylone C2 and PCM based on it with increasing temperature monotonously increases to a temperature of 489 K (Fig. 8, *a*). Upon reaching the specified temperature, there is a jump in heat capacity in the range until the temperature reaches 548 K.

It has been established that the introduction of 5 wt% TEG in Phenylone C2 leads to a slight increase in the coefficient of thermal conductivity, only by 4 % (Fig. 8*b*). With an increase in the concentration of filler up to 15 wt %, there is a significant increase in the thermal conductivity coefficient, by 32.6 % (from 0.49 to 0.65 W/m·K). Further increase in the amount of filler to 25 wt% leads to insignificant growth of the studied indicator, compared with filling by 15 wt%, by only 6.1 %. This trend is characteristic of the temperature range from 323 to 498 K. It should be noted that in the temperature range from 523 to 573 K, there is a slight increase in the thermal conductivity coefficient, regardless of the filler content.

The results of the study of the effect of the filler on the change in relative elongation on temperature are shown in Fig. 9.

The introduction of 5 and 15 wt % TEG in the structure of Phenylone C2 leads to a decrease in the relative elongation of PCM compared to the unfilled source material. The nature of the specified curves for Phenylone C2 and PCM with the specified content are similar to each other. At the same time, in the case of a filler concentration of 25 wt%, there is a significant decrease in the relative elongation and a significant change in the nature of the dependence of the studied indicators.

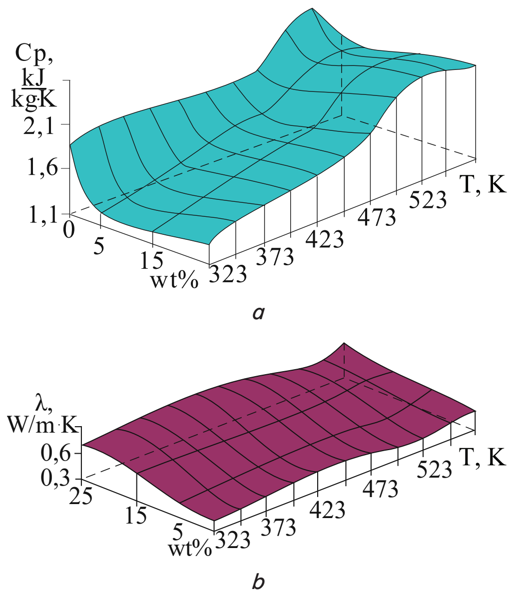

Fig. 8. Influence of the temperature and content of thermally expanded graphite on the thermophysical characteristics of Phenylone C-2 and polymer-composite materials based on it: *a* — specific heat capacity; *b* — coefficient of thermal conductivity

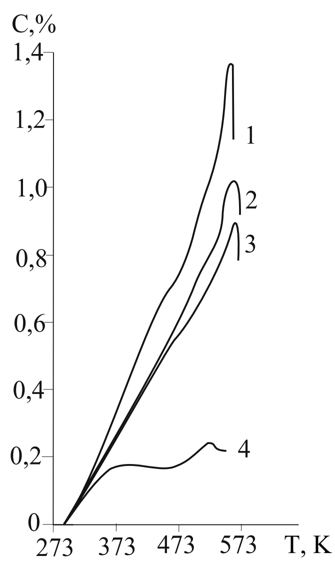

Fig. 9. Dependence of relative elongation on temperature: 1 — Phenylone C-2; 2 — Phenylone C2+5 wt% thermally expanded graphite; 3 — Phenylone C2+15 wt% thermally expanded graphite; 4 — Phenylone C2+25 wt% thermally expanded graphite

The effect of fillers on the tribological properties of Phenylone C2 and PCM based on it was investigated under the condition of friction without lubrication. At the same time, the pressure on the sample did not exceed 2 MPa. Such values were chosen based on the fact that the increase in pressure on samples from Phenylone C2 to 2.5...3 MPa leads to its catastrophic wear. The results of the effect of the filler concentration on the friction coefficient of PCM are shown in Fig. 10.

The introduction of TEG in the amount of 5 wt% leads to a significant reduction in the friction coefficient, from 0.54 (unfilled Phenylone C2) to 0.38 and 0.41, respectively, for fillers HL-2 and B (Fig. 10). Subject to filling by 15 wt%, there is a decrease in the coefficient of friction, compared with filling by 5 wt%, by 26.3 and 21.9 %, respectively, for fillers HL-2 and B. Our results of the filler effect on the friction coefficient of PCM confirm the advantage of TEG HL-2, in comparison with TEG B. The introduction of filler in the amount of 25 wt% makes it possible to slightly reduce the coefficient of friction, compared with filling by 15 wt%.

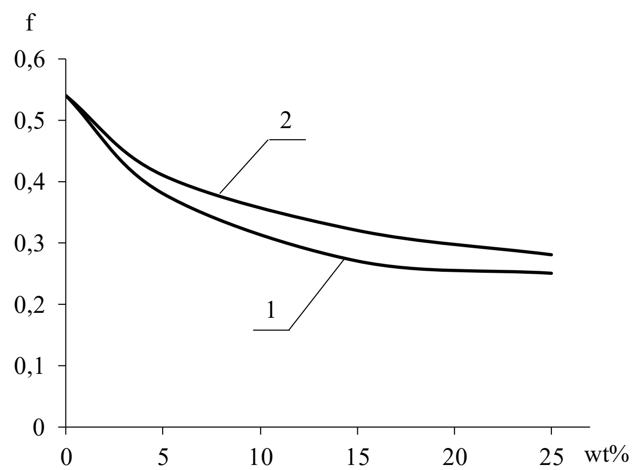

Fig. 10. Dependence of the friction coefficient of polymer-composite material based on Phenylone C2 on the content (wt%) of thermally expanded graphite: 1 — filler HL-2; 2 — filler B (P=2 MPa)

Taking into account our results regarding the influence of the filler on the physical and mechanical characteristics, it is taken that the basic concentration of the filler is 15 wt %. The introduction of TEG HL-2 in Phenylone C2 makes it possible to obtain PCM, which has higher physical and mechanical characteristics and a lower coefficient of friction, compared with the filler TEG B. Therefore, for detailed studies of the tribological properties of PCM, under different friction conditions, a material consisting of Phenylone C2 filled with 15 wt% of TEG HL-2 was chosen.

Studies of the tribological properties of the designed PCM based on Phenylone C2, subject to friction without lubrication, have established that the amount of wear during friction on steel 45 and copper changes symbatically (Fig. 11).

When using a counter-body made of steel 45, the amount of wear is reduced to a pressure of 4 MPa, reaching a value of 0.54 mg. A similar result was recorded at a pressure of 5 MPa. A further increase in pressure to 6–7 MPa leads to a sharp increase in the amount of wear by 24 50 %. The smallest amount of wear under the condition of PCM friction without lubrication on copper is achieved at a pressure of 5 MPa (Fig. 11). At the same time, an increase in pressure above the specified value leads to a sharp increase in wear.

The coefficient of friction under the condition of friction on the specifed counter-bodies also decreases with increasing pressure, reaching a minimum value of 0.11, at a pressure of 6–7 MPa. The friction mode is limited by a pressure of 7 MPa since the temperature of a tribojunction under such conditions reaches 107–112 °C.

The results of the study of the effect of pressure on the amount of wear and friction coefficient of PCM based on Phenylone C2 filled with 15 wt% TEG HL-2 for friction with lubrication are shown in Fig. 12. It was established that the amount of wear, subject to friction on a counter-body of steel 45, with an increase in pressure gradually increases to a value of 0.4 mg, stabilizing at a pressure of 12 MPa. A further increase in pressure to 15 MPa does not affect the amount of wear when rubbing on steel 45.

The dependence of changes in the amount of wear during friction of PCM on a counter-body of copper has a different character (Fig. 12). The increase in pressure from 1 MPa to 4 MPa causes a significant increase in the amount of wear, reaching a maximum value of 0.85 mg, precisely at a pressure of 4 MPa. A further increase in pressure leads to a gradual decrease in the amount of wear, the minimum value of which is achieved at P=12 MPa. Increasing the pressure to 15 MPa, as well as for friction on steel 45, does not affect the amount of wear.

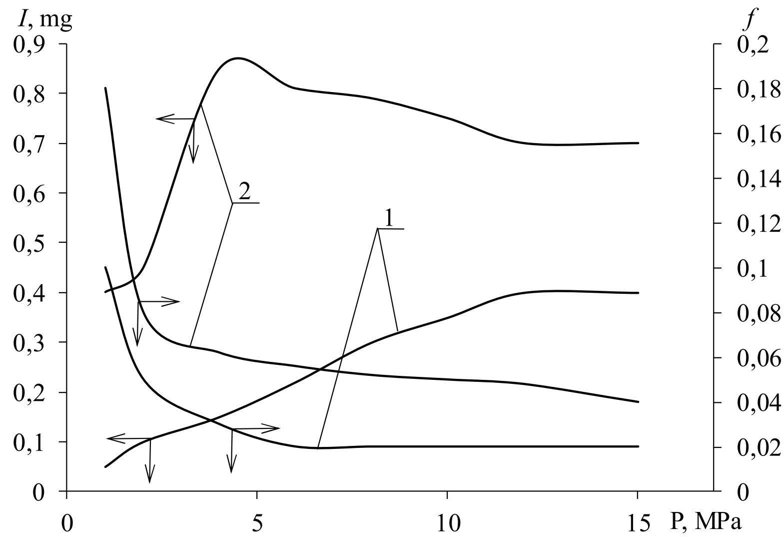

Fig. 12. Dependence of the wear value and friction coefficient of the polymer-composite material based on Phenylone C2 filled with 15 wt% of thermally expanded graphite on pressure under the condition of friction with lubrication for: 1 – steel 45; 2 – copper

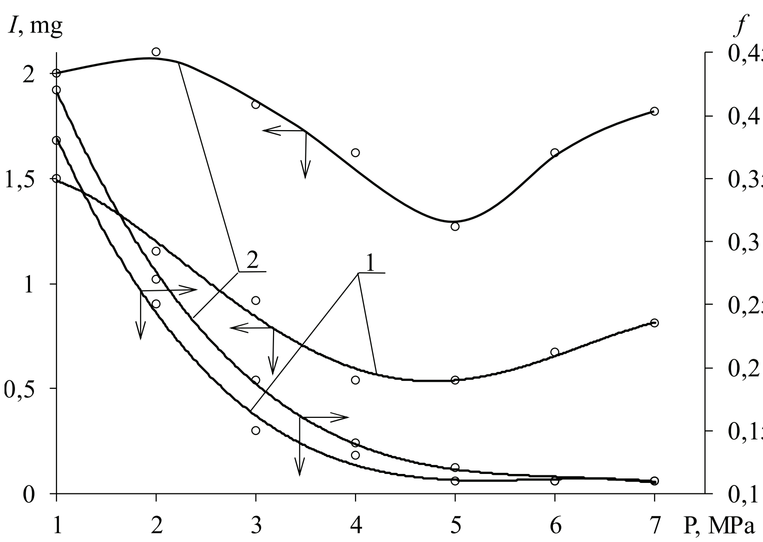

Fig. 11. Dependence of the wear value and friction coefficient of the polymer-composite material based on Phenylone C2 filled with 15 wt% of thermally expanded graphite on pressure, subject to friction without lubrication, for: 1 – steel 45; 2 – copper

The dependence of the coefficient of friction on pressure is similar for both types of counter-bodies (Fig. 12). Initially, there is a rapid decrease in it in the region from 1 to 3...4 MPa, followed by stabilization with a slight deviation to a maximum pressure of 15 MPa. The temperature in the friction zone at a maximum pressure did not exceed 47 °C.

6. Discussion of results of investigating the characteristics and properties of polymer-composite materials

When introducing TEG of 15 wt% or more into the matrix, there is a process of its local accumulation and delamination of PCM (Fig. 3, *b*, *c*), in the direction of parallel application of force during processing. This can be explained by the effect of adhesion of filler fibers to each other, which, when the sample volume decreases (during compression), intersect with each other and form local clusters. During heat treatment (sintering) of the sample, the binder is not able to fully penetrate into significant accumulations of filler, and as a result, it cannot form a monolithic structure of PCM. The decrease in impact strength (Fig. 6) with an increase in the volume of injected filler is caused by the fragile structure of TEG itself. Curves σ–ε (Fig. 7, curves 3, 4), when filling Phenylone C2 with TEG in the amount of 15 and 25 wt%, have a shape characteristic of type II curves. Such curves have a rectilinear region associated with elastic deformation, and a parabolic region characterizing homogeneous plastic deformation.

The introduction of TEG, in the amount of from 5 to 15 wt % in Phenylone C2 leads to a decrease in heat capacity (Fig. 8, *a*), which is due to a decrease in the mobility of macromolecules due to the transition of a certain number of them into the boundary layers. With an increase in the concentration of filler up to 25 wt %, there is a slight increase in the heat capacity of PCM. This effect is due to the fact that the number of macromolecules that have received freedom due to the loosening effect is much greater than the number of macromolecules that reduced mobility during the transition to the boundary layers. A significant increase in the coefficient of thermal conductivity (Fig. 8, *b*) with the introduction of the filler in the amount of 15 wt% or more is due to the emergence of the mechanism of percolation thermal conductivity. According to it, when a certain concentration is exceeded, the filler particles come into contact with each other, forming thermal conductivity channels in PCM.

The coefficient of friction of the designed PCM, provided that it works without lubrication, decreases to a certain value with increasing pressure, and then stabilizes (Fig. 11). Unlike [10], where in order to reduce the friction coefficient of PCM based on C2, it was necessary to carry out complex and energy-intensive preparation of the filler, this result can be achieved by the introduction of TEG, without prior preparation. This is explained by the fact that with the wear of PCM, TEG from its structure, falling on the counter body, reduces the coefficient of friction, and when a certain concentration of graphite is reached, its stabilization is observed.

The proposed technology of obtaining polymer-composite materials, based on Phenylone C2 and TEG in the electromagnetic field, provides sufficient physical and mechanical characteristics, tribological properties, and low cost of finished articles (parts).

The limiting factor of the proposed method of mixing the components of the polymer-composite material is the impossibility of obtaining a monolithic PCM, with a concentration of TEG of more than 15 wt%. The disadvantages of the study include the influence of the technical characteristics of electromagnetic mixers on the quality of the resulting PCM. In the future, it is necessary to carry out detailed studies into the effect of the filler on the characteristics and properties of PCM based on Phenylone C2 and TEG in increments of 1…2 wt% in the range of 5…20 wt%.

Thus, we can recommend PCM, based on Phenylone C2 with a concentration of TEG HL-2 of 15 wt %, as a structural material for movable connections of machines and mechanisms. In the future research, in this area, it is necessary to pay attention to the effect of the duration of mixing of PCM components on the quality of their distribution in finished articles (parts).

7. Conclusions

1. It was established that when thermally expanded graphite was introduced into Phenylone C2 in the amount of 5 wt%, the latter is evenly distributed. Further increase in the concentration of filler to 15 wt % leads to the emergence of small local clusters. With the introduction of 25 wt%, the delamination of polymer-composite material is observed, which prevents the production of high-quality monolithic material during processing into finished articles (parts).

2. It was found that in comparison with the unfilled Phenylone C2, the physical and mechanical characteristics of composites, based on it, filled with TEG in the amount of 5…25 wt%, decrease. The introduction of TEG HL-2 in the amount of 5 wt% leads to a slight decrease in the magnitude of the fracture stress and the modulus of elasticity at compression, by 3.1 % and 3.3 %, respectively. At the same time, subject to the introduction of TEG B, there is a significant decrease in the magnitude of the destruction stress during compression, by 22.7 %. The introduction of TEG in the amount of 5 wt% in Phenylone C2 leads to a decrease in heat capacity by 34 %. A further increase in the concentration of the filler does not significantly affect the heat capacity of the PCM. The introduction of TEG in Phenylone C2 leads to an increase in the thermal conductivity coefficient in the entire range of the studied temperatures. When operating the designed PCM under a dry friction mode, at a pressure of 2 MPa, the friction coefficient is reduced by 53.7 %. The smallest amount of wear under the condition of friction without lubrication, regardless of the nature of the counter-body, is achieved at a pressure of 5 MPa. It has been established that the amount of wear, subject to friction with lubrication, gradually increases with increasing pressure to 12 MPa. A further increase in pressure to 15 MPa does not affect the amount of wear, regardless of the material of the counter-body. The amount of wear at friction on copper is 75 % higher compared to friction on the counter-body of steel 45. It was established that the optimal concentration of TEG in PCM, which provides sufficient physical and mechanical characteristics and high tribological properties, is 15 wt %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

References

1. Hsissou, R., Seghiri, R., Benzekri, Z., Hilali, M., Rafik, M., Elharfi, A. (2021). Polymer composite materials: A comprehensive review. Composite Structures, 262, 113640. doi: https://doi.org/10.1016/j.compstruct.2021.113640
2. Dykha, A., Svidersky, V., Danilenko, I., Bilichenko, V., Kukurudzyak, Y., Kirichenko, L. (2020). Design and study of nanomodified composite fluoropolymer materials for tribotechnical purposes. Eastern-European Journal of Enterprise Technologies, 5 (12 (107)), 38–48. doi: https://doi.org/10.15587/1729-4061.2020.214533
3. Derkach, O., Artemchuk, V., Muranov, E. (2017). Regarding to issue of machinability processing the polymeric composites for seeding machines. Visnyk Kharkivskoho natsionalnoho tekhnichnoho universytetu silskoho hospodarstva imeni Petra Vasylenka, 181, 157–166. Available at: http://nbuv.gov.ua/UJRN/Vkhdtusg_2017_181_27
4. Aulin, V., Derkach, O., Makarenko, D., Hrynkiv, A., Pankov, A., Tykhyi, A. (2019). Analysis of tribological efficiency of movable junctions “polymericcomposite materials – steel.” Eastern-European Journal of Enterprise Technologies, 4 (12 (100)), 6–15. doi: https://doi.org/10.15587/1729-4061.2019.176845

5. Gilbert, M. (2017). Aliphatic Polyamides. Brydson's Plastics Materials, 487–511. doi: https://doi.org/10.1016/b978-0-323-35824-8.00018-9
6. Krasinskyi, V., Suberlyak, O., Sikora, J., Zemke, V. (2021). Nanocomposites based on polyamide-6 and montmorillonite intercalated with polyvinylpyrrolidone. Polymer-Plastics Technology and Materials, 60 (15), 1641–1655. doi: https://doi.org/10.1080/25740881.2021.1924201
7. Kabat, O., Sytar, V., Sukhyy, K. (2018). Antifrictional Polymer Composites Based on Aromatic Polyamide and Carbon Black. Chemistry & Chemical Technology, 12 (3), 326–330. doi: https://doi.org/10.23939/chcht12.03.326
8. Burya, A. I., Dudin, V. Yu., Burya, A.A., Kholodilov, O. V. (2002). Friction and wear of the aromatic polyamide filled with thermally disintegrated graphite. Trenie i Iznos, 23 (3), 296–299. Available at: https://www.researchgate.net/publication/292487459_Friction_and_wear_of_the_aromatic_polyamide_filled_with_thermally_disintegrated_graphite
9. 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. doi: https://doi.org/10.31891/2079-1372-2020-96-2-42-48
10. Ivanochkin, P. G., Dolgopolov, K. N., Danilchenko, S. A. (2018). Creation of Oil-Filled Composites of Tribotechnical Purpose Based on Aromatic Polyamide Phenylone C-2. Solid State Phenomena, 284, 14–19. doi: https://doi.org/10.4028/www.scientific.net/ssp.284.14
11. Ivanochkin, P. G., Danilchenko, S. A., Novikov, E. S. (2016). Antifriction Composites Based on Phenylone C2 for Work under Conditions of Dry Friction. Procedia Engineering, 150, 520–526. doi: https://doi.org/10.1016/j.proeng.2016.07.033
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. doi: https://doi.org/10.15587/1729-4061.2021.238452