

This paper reports a comprehensive laboratory study into the thermophysical, physical-mechanical characteristics, and tribological properties of the designed composite materials based on polytetrafluoroethylene. In the structures of machines and mechanisms, a significant role belongs to the tribological conjugations made from polymeric and polymer-composite materials. The reliability of machines, in general, depends to a large extent on the reliability of movable connections. Composite materials of nonmetallic origin have a low cost, they are resistant to most aggressive chemicals and are capable of operating under conditions without lubrication. It was established that the characteristics and properties of materials must be adapted to the working conditions of separately considered tribological conjugations.

The mechanisms of thermal destruction have been established, both in the basic material and the carbon fiber based on it. It was found that carbon fiber, regardless of its content (quantity) in the polymer-composite material based on polytetrafluoroethylene, is mainly oriented perpendicular to the force application plane. It was found that with an increase in the carbon fiber content from 10 to 40 % by weight, the heat capacity decreases by 16–39 % compared to the main material. The optimal operating modes for the designed composite materials have been substantiated on the basis of a pv factor: under a dry friction mode – up to 4 MPa·m/s; at friction with lubrication – up to 36.4 MPa·m/s. The dependence has been established of the friction coefficient on the operating modes of a composite material based on polytetrafluoroethylene containing 20 % by weight of carbon fiber when lubricated with oil and water.

The results reported here make it possible to synthesize the physical-mechanical characteristics and tribological properties of composite materials in accordance with the required modes of tribological conjugation

Keywords: polytetrafluoroethylene, polymer-composite material, carbon fiber, tribological conjugation, physical-mechanical characteristics, tribological properties

DETERMINING THE EFFECT OF A FILLER ON THE PROPERTIES OF COMPOSITE MATERIALS BASED ON POLYTETRAFLUOROETHYLENE FOR THE TRIBOLOGICAL CONJUGATIONS IN MACHINES AND MECHANISMS

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1. Introduction

The reliability of machines and mechanisms largely depends on the reliability of movable connections. In their structures, roll or slide bearings are used as rotating elements, equipped, if necessary, with sealing elements. Therefore, improving the reliability of these elements is a key task of ensuring a high technical level of machines. One of the solutions to this problem is the introduction of polymer-composite materials (PCMs) for structural purposes [1, 2]. The development of PCM application in mechanical engineering is predetermined by their reliability and capability to work in tribological conjugations operated under conditions without lubrication [3, 4], at low and high temperatures, by the resistance to aggressive chemicals, etc. One of the polymeric materials, which has unique physical-mechanical characteristics and tribological properties and is widely used in tribological conjugations, is polytetrafluoroethylene (PTFE). The main direction to improve the physical, mechanical, and tribotechnical characteristics of PTFE is its modification

by various fillers. There are technologies for creating PCMs based on PTFE, which can significantly improve its characteristics but the cost of such materials usually exceeds the economic effect of their introduction. That is why devising new technologies to manufacture PCMs at insignificant costs is a relevant task of materials science and industrial engineering. The study of the characteristics and properties of the new PCMs is the basis for designing materials with programmed properties, which opens the way to the improvement of the structures of tribological conjugations in machines and mechanisms.

2. Literature review and problem statement

Among the current directions to enhance the physical-mechanical characteristics of PTFE, the main one is the introduction of fibred and dispersed fillers into its structure. Paper [5] reports the results of studying the characteristics of a PCM material based on PTFE and fibrous fillers. It was established

that carbon fibers (CFs) perform the function of reinforcement and provide an increase in the physical-mechanical characteristics by up to 3...5 times compared to the starting material. However, the issues related to the increase in the adhesion of the filler and the main material remained unresolved. The likely reason is the objective difficulties associated with the cost part of the preparation of PCM components before mixing. One of the options for overcoming the difficulties related to the low and unstable adhesion of the filler with the main material is to process CF before introducing it into the PTFE matrix. This approach is used in work [6], in which it is proposed to use thermal oxidation treatment and grinding CFs with a crusher in a vacuum environment. The cited work has found that the thermal oxidation and treatment of CFs with liquid nitrogen contribute to a slight increase in the characteristics of resulting PCMs (up to 8 %). Vacuum processing of CFs during grinding produces a significant effect but the technological process is difficult to implement and requires significant energy costs. In work [7], to increase the adhesion of PCM components based on PTFE, the introduction, in addition to carbon fiber, of dispersed polyamide particles 6 was proposed. However, the introduction of small-sized fillers leads to an increase in the energy intensity of the mixing process, and, as a result, to an increase in the cost of the material obtained. One of the options to reduce the cost of PCM production is the application of mechanical activation in the air environment [8]. That has made it possible to reduce the wear intensity at some concentrations of the filler by 5...6 times. However, the disadvantage of the proposed compositions is a decrease in the tensile strength, depending on the PCM composition, by up to 25 %. Modifying polymers with silicates, which leads to the transformation of PCM properties, is proposed in work [9]. The authors of [10] suggest exposing the finished composition during its baking (processing) to radiation in order to improve the physical-mechanical characteristics. The application of radiation and chemical irradiation of PCMs, based on PTFE, leads to the formation of new microstructures, which contributes to the improvement of the physical-mechanical characteristics and the tribotechnical properties of composites. However, the issue related to the widespread introduction of the proposed technology into production remained unresolved. The likely reason is the objective difficulties associated with the cost component of the specialized equipment for irradiating the composition when it is baked. One of the options for solving problems associated with increasing the characteristics of PTFE, at insignificant additional costs for the technological process of processing, is the introduction, in addition to CFs, of special dispersed fillers (nanopowders). In work [11], it was proposed to use zirconium oxide (dioxide) as fillers, in addition to CFs. It has been shown that the introduction of such a filler makes it possible to improve the physical-mechanical characteristics of PTFE, in particular, tensile strength, by more than three times. However, insignificant concentrations of zirconium dioxide, which do not exceed 1...2 % by weight, create additional obstacles regarding the uniform distribution of the filler in the matrix. This issue was not paid due attention in work [11]. In addition, the cost of nanopowders is quite high, which leads to a rise in the price of the modified PCM. An option to overcome the corresponding difficulties may be the utilization of industrial waste. This approach is applied in [12]. As a filler, it is proposed to use silicon recycled from industrial waste. The introduction of the filler has made it possible to improve the physical-mechanical characteristics and tribological properties of PCM based on PTFE. However, the research was carried out at a maximum

pressure of 1.5 MPa, which limits the application scope of such materials.

Most scientific research is aimed at improving the physical-mechanical characteristics of PCMs, while, for a significant number of movable connections, such high values of individual indicators are not required as they exceed the necessary ones tenfold. Based on the analysis of technologies for obtaining PCMs, it was established that known technologies either do not make it possible to get the desired result or are impractical from an economic point of view. That is why it is a relevant task to tackle the development of a technologically affordable and economically inexpensive technique to produce PTFE-based PCMs for the tribological conjugations in machines and mechanisms. This could resolve the issue associated with the inconsistency between PCM characteristics and its cost.

3. The aim and objectives of the study

The purpose of this study is to determine the effect of the filler on the characteristics and properties of composite materials obtained using simple processing technology for finished products.

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

- to analyze the microstructure of the designed PCMs, to substantiate the peculiarities in the distribution of the filler in the matrix;
- to investigate the thermophysical, physical-mechanical characteristics, and tribological properties of experimental samples of the designed PCMs, based on PTFE and CF.

4. The study materials and methods

Our study involved the samples of PCMs made on the basis of PTFE and the filler – CF. Counter-body was a disk made from steel of grade 45 (1.1191, EN 10083). The technology of preparing the PCM components implied drying the CFs at a temperature of 200 °C for 2 hours. We mixed the PCM components in a dry state, at the installation ABC-150K, which is carried out for 40...60 seconds in a rotational electromagnetic field with a magnitude of the magnetic induction of 0.09...0.14 Tesla using ferromagnetic elements. The latter were extracted from the polymeric composition by magnetic separation. The resulting composition was processed into samples by direct compression pressing (pressure, 40 MPa). The samples for our study had the following dimensions: diameter, 9 mm; height, 18 mm.

The thermal conductivity at room temperature was determined in accordance with GOST 15173-70 at the device ITEM-1M. Samples made of carbon fiber with a diameter of 15 and a height of 3 mm were used. The device was calibrated using reference measures of copper and Plexiglas (whose height and diameter were 1 and 15 mm, respectively). Then we measured the height and diameter of the examined sample, after which it was installed in the plate of the heat meter, having previously lubricated contact surfaces with a silicone lubricant. Controls located on the front panel of the measuring unit were used. Before the test, the dimensions of the height and diameter of the were entered into the measuring unit. Then the thermal block was lowered and the thermal conductivity was automatically measured, whose value was read from the digital display. The arithmetic mean of the thermal conductivity, derived from at least 10 measurements, which differed by no more than 1 %, was adopted as the result.

The temperature conductivity was calculated from the following formula:

$$a = \frac{\lambda}{C_p \rho}, \quad (1)$$

where a is the thermal diffusivity, m^2/s ;

λ is the thermal conductivity coefficient, $\text{W}/(\text{m}\cdot\text{K})$;

C_p is the specific heat capacity, $\text{kJ}/\text{kg}\cdot\text{K}$;

ρ is the sample density, kg/m^3 .

To treat the experimental data, we used a program for calculating thermophysical characteristics employing the Microsoft Excel software (USA).

Differential thermal analysis was performed at the derivatograph Q-1500D (Fig. 1) (Hungary). Tests were carried out in special ceramic crucibles in the air in the temperature range of 298...1,273 K. The temperature rise rate was $5^\circ\text{C}/\text{min}$. Al_2O_3 was used as a reference substance, its amount was 100 mg. A batch of carefully crushed parts from PCM was placed in a special test chamber 1 and, with the help of a control unit, we set the rate of temperature rise. The tests were carried out automatically. The thermogravimetry analysis results were obtained using registration unit 3 with the output to special form 4, which was then processed.

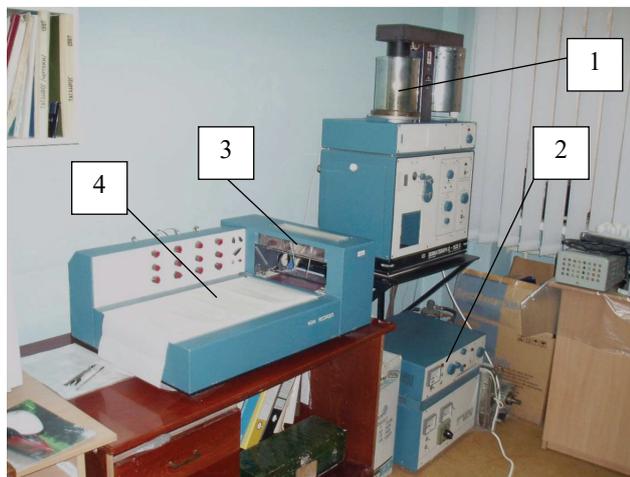


Fig. 1. Derivatograph Q-1500D by the system of F. Paulick, J. Paulick, L. Erdey, MOM type: 1 – test camera; 2 – control unit; 3 – block of registration of results; 4 – registration form

During the tests, temperatures were recorded at which 0, 5, and 30 % of the material's mass were lost; in addition, temperatures were recorded at which the maximum speed of material destruction was observed.

We studied the surface of friction and the distribution of carbon fibers in the polymeric matrix using the NEOFOT 30 microscope (Fig. 2). In this case, images of the examined objects from the NEOFOT 30 microscope were transferred to big screen 1 for more convenient visual control, and, to a photo plate, through screen 2, for photographing.

We determined the friction coefficient at the wear and friction machine SMC-2 according to a procedure from [4].

Before the start of each test, in order for the friction surfaces of the samples to have a parallel shape and the contact area to be at least 85 %, the samples were rubbed.

The friction coefficient of the slip was determined from the following formula:

$$f = \frac{M_T}{P \cdot \Delta}, \quad (2)$$

where M_T is the torque that occurs on the disk, $\text{N}\cdot\text{m}$;

P is the load on a sample, N ;

Δ is the paper step, m . For all experiments, it is the same, $\Delta=0.0025 \text{ m}$.



Fig. 2. Optical microscope NEOFOT 30: 1 – screen for visual analysis, 2 – screen for photographing

The temperature in the friction zone was determined with the help of chromel-alumel electronic thermocouple "Thermometer 301 Type K". The hole for measuring the temperature was at a depth equal to half the diameter of the sample, at a distance of 1 mm from the friction surface. The data were acquired every 5 minutes. The pressure in the tribological conjugation was changed in the range from 1 MPa to 14 MPa, the slip speed – 0.8...2.6 m/s .

The PCM strength properties were determined at the FP-100 test machine, according to GOST 4651-82. To study the compression strength boundary, samples with a diameter of 10 and a height of 15 mm were used. In this case, the base planes of the samples must be parallel within 0.1 % in the direction that is perpendicular to the load application.

The compression strength limit (σ_s) was calculated from the following formula:

$$\sigma_s = P/A, \quad (3)$$

where P is pressure, MPa , A is the minimum area of the cross-section of the sample, mm^2 ;

$$A = \pi d^2/4, \quad (4)$$

where d is the diameter of the sample, mm .

The relative compression deformation (ϵ) was calculated from the following formula:

$$\epsilon = \Delta h_p \cdot 100/h_0, \quad (5)$$

where Δh_p is the value of reducing the height of the sample, mm ; h_0 is the initial height of the sample, mm .

The impact viscosity was determined at the pendulum hammer KM-0.4 by the method of Charpy according to GOST 4647-80 at a temperature of $23 \pm 2^\circ\text{C}$ and relative air humidity of $50 \pm 5\%$.

The essence of the method was to test when a sample, resting on two supports (the distance between the supports is 40 mm), is destroyed when the pendulum hits it, and the strike line is in the middle between the supports.

The impact viscosity of samples with PCM was calculated from the following formula:

$$a_n = \frac{J_n}{b \cdot s \cdot 1,000}, \tag{6}$$

where J_n is the impact energy used on the destruction of the sample, kJ/(kg·cm²), it is registered on the digital display of the device; b is the width of the sample in its middle, mm; s is the thickness of the sample in its middle, mm.

We determined the possible mechanism of the process and calculated the kinetic parameters of the thermal destruction of PTFE and PCM on its basis using integrated kinetic equations of various mechanisms of heterogeneous processes (Table 1) [13].

The criteria for choosing a mathematical model were the correlation coefficient r in the coordinates of the Arrhenius equation and the minimum of the S function:

$$s = f\{\alpha / (\tau), T(\tau), \Delta T(\tau), E, Z\}, \tag{7}$$

$$S = \sqrt{\sum_{i=1}^m \frac{(\alpha_{\text{exp}} - \alpha_{\text{calc}})^2}{m}}, \tag{8}$$

where α is the value of the degree of transformation; α_{exp} , α_{calc} are the experimental and estimated values of the degree of transformation; τ is time; m is the amount of experimental data; T – temperature; E is the activation energy; Z is the pre-exponent multiplier.

The kinetic equations of various heterogeneous processes allow us, based on the experimental and calculated data, to substantiate the process of thermal destruction of the newly created PCMs.

Kinetic equations for different mechanisms of heterogeneous processes [13]

Function	Equation	A process that determines the speed of reaction	Mathematical model
N_1	$k\tau = \alpha$	Nucleation by static law, the rate of nucleation determines the process rate, $n=1$	(9)
N_2	$k\tau = 2\alpha^{\frac{1}{2}}$	Nucleation by static law, the rate of nucleation determines the process rate, $n=2$	(10)
R_2	$k\tau = 2 \left[1 - (1 - \alpha)^{\frac{1}{2}} \right]$	Reaction at the interphase, cylindrical symmetry	(11)
R_3	$k\tau = 3 \left[1 - (1 - \alpha)^{\frac{1}{3}} \right]$	Reaction at the interphase, spherical symmetry	(12)
F_1	$k\tau = -\ln(1 - \alpha)$	Random nucleation, one nucleus per particle	(13)
A_2	$k\tau = 2 \left[-\ln(1 - \alpha) \right]^{\frac{1}{2}}$	Random nucleation, the Abraham-Erofeev equation, $n=2$	(14)
A_3	$k\tau = 3 \left[-\ln(1 - \alpha) \right]^{\frac{1}{3}}$	Random nucleation, the Abraham-Erofeev equation, $n=3$	(15)

5. The results of studying the characteristics and properties of polymeric-composite materials

5.1. The results of studying the microstructure of the designed polymeric-composite materials

Studying the microstructure of PTFE-based PCMs (Fig. 3, 4) has made it possible to find out that, regardless of the content (quantity) of CFs, they are mainly oriented perpendicular to the place of force application, zone 1 (Fig. 3).

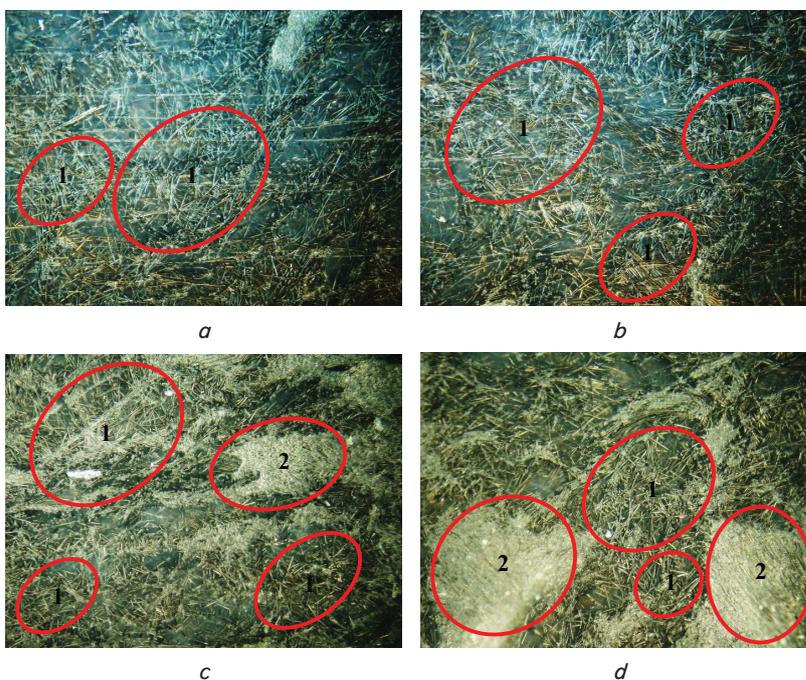


Fig. 3. Microstructure in the intersections of the perpendicular direction of pressing polymeric-composite materials based on polytetrafluoroethylene filled with carbon fibers: a – 10 % by weight; b – 20 % by weight; c – 30 % by weight; d – 40 % by weight, $\times 150$

In addition, our analysis of the photographs reveals that as the content of CF increases, this trend does not change. As for the quality of the distribution of the filler, with an increase

Table 1

in the content of CF to 30 and 40 % by weight, there is a stratification of the PCM in the plane parallel to the direction of pressing, zone 1 (Fig. 4).

At magnification $\times 300$, one can see that only part of CFs has a chaotic distribution in the matrix, and the white delamination spots are actually the sites of CF concentration, zone 1 (Fig. 5).

A significant concentration of CFs (exceeding 30 % by weight) leads to the PCM stratification during its pressing, and, as a result, when heated, a monolithic PCM is not formed.

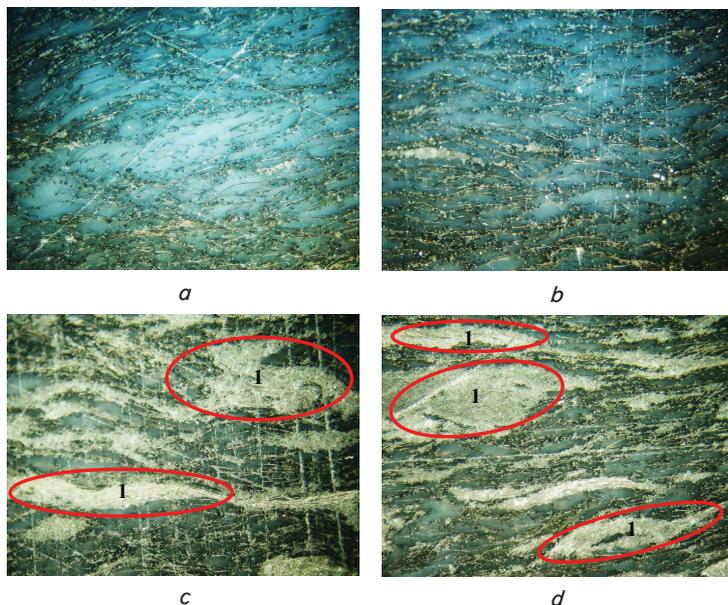


Fig. 4. Microstructure in the intersections of parallel pressing direction of polymeric-composite materials based on polytetrafluoroethylene filled with carbon fibers: *a* – 10 % by weight; *b* – 20 % by weight; *c* – 30 % by weight; *d* – 40 % by weight, $\times 150$

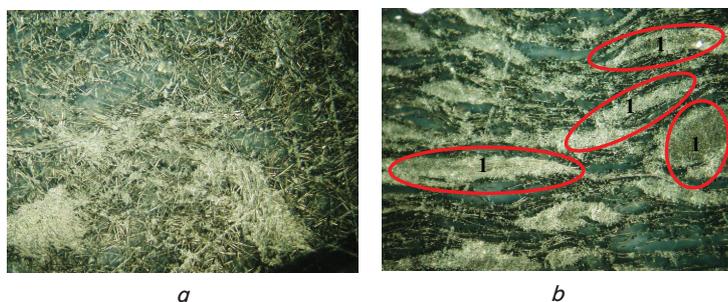


Fig. 5. Microstructure of the polymeric-composite materials based on polytetrafluoroethylene, which contains 40 % by weight of carbon fibers: *a* – perpendicular to the pressing direction; *b* – parallel to the direction of pressing, $\times 300$

5. 2. The results of studying the thermal, physical-mechanical characteristics, and the tribological properties of the designed composite materials

Most often, the performance of materials during heating is characterized by heat resistance [13], the main method for determining which is differential thermal analysis. Data on the thermogravimetric analysis of PTFE and PCMs based on it are given in Table 2.

Table 2

Heat resistance of PTFE and PTFE-based PCMs

Material	T_{10}	T_{20}	T_{30}
PTFE	889	920	924
PTFE +10 % CF	864	894	907
PTFE +20 % CF	874	899	908
PTFE +30 % CF	880	900	908
PTFE +40 % CF	878	895	914

Note: T_{10} , T_{20} , T_{30} – temperature at 10, 20, 30 % weight loss, K

Based on our data, it was found that the PCM heat resistance decreased compared to the binder.

As regards the curves “weight loss–temperature” (Fig. 6), their contours are similar, that is, the decomposition of the reinforced fluoroplastic proceeds similarly to a pure one.

At the first stage, for the materials studied, there is a gradual decrease in mass, then there is a monotonous increase in the loss of mass of the materials with increasing temperature. Intensive destruction of the examined materials, accompanied by a significant loss of mass, begins after 853 K. In order to choose the optimal kinetic model to describe the process of thermal destruction of PTFE and PTFE-based PCMs, we have considered the possibility of using mathematical models of various heterogeneous processes [13].

The results of calculating the initial parameters of the PTFE thermal destruction: a correlation coefficient, a minimum of the function, activation energy, a pre-exponent multiplier, computed by the software installed on a PC, are given in Table 3.

Table 3

Estimated kinetic parameters of the non-isothermal process of PTFE thermal decomposition

Process mathematical model	R	$S \cdot 10^{-2}$	$E_{act.}$, kJ/mol	lgZ
(9)	0.948	9.04	223.79	9.19
(10)	0.943	8.58	106.39	2.79
(11)	0.959	5.96	243.83	10.42
(12)	0.962	5.35	250.97	10.86
(13)	0.968	4.43	265.89	11.78
(14)	0.950	7.25	81.256	1.49
(15)	0.965	33.9	127.45	4.09

It was established that the highest values of the correlation coefficient and the minimum value of S correspond to kinetic equation (13). Thus, based on the data from Table 3, it was established that the process of PTFE thermal destruction is best described by the first-order equation. As for PCMs, the process of their thermal destruction is best characterized by an equation describing the process of nucleation according to the power law, specifically, equation (9), at the kinetic parameters given in Table 4.

Table 4

Estimated kinetic parameters of the non-isothermal process of thermal decomposition of PCMs based on PTFE

Material	R	$S \cdot 10^{-2}$	$E_{act.}$, kJ/mol	lgZ
PTFE+10 % CF	0.994	2.47	204.61	8.06
PTFE+20 % CF	0.989	4.73	197.26	7.65
PTFE+30 % CF	0.998	2.62	224.81	9.31
PTFE+40 % CF	0.998	2.05	197.24	7.68

The results of our study of changes in the specific heat capacity of PCMs based on PTFE on CF content are shown in Fig. 7.

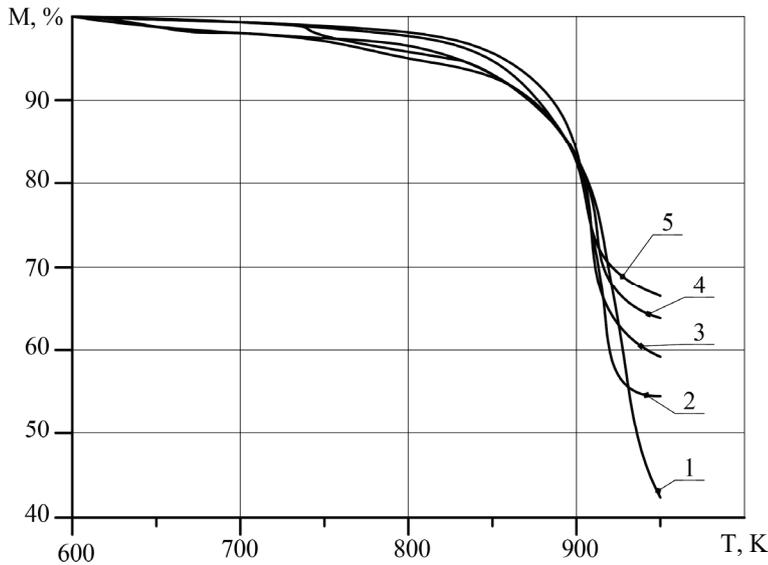


Fig. 6. The curves of thermogravimetric analysis of polytetrafluoroethylene and the composite materials based on it:
 1 – polytetrafluoroethylene;
 2 – polytetrafluoroethylene+10 wt % carbon fiber;
 3 – polytetrafluoroethylene+20 wt % carbon fiber;
 4 – polytetrafluoroethylene+30 wt % carbon fiber;
 5 – polytetrafluoroethylene+40 % carbon fiber

The increase in the coefficient of thermal conductivity in comparison with the starting material occurs only in the PCM reinforced with 40 % by weight of CFs – by 10 % (Table 5).

The thermal conductivity coefficient decreases by 15.8 % when 10 % by weight of CF is introduced in PTFE. A further increase in the concentration of the filler is accompanied by an increase in the specified indicator, and

even exceeding it, compared to the non-filled PTFE, at 40 % by weight.

Table 5
 Effect of CF content on the thermal conductivity coefficient of PTFE-based PCMs

CF content, % by weight				
0	10	20	30	40
0.164	0.138	0.141	0.152	0.182

It was established that the introduction of heat-resistant CFs in PTFE makes it possible to increase the heat resistance by Wick: with an increase in the Ural fiber content in a polymeric binder, this thermophysical indicator increases by 60...140 °C. The maximum increase in heat resistance occurs when reinforcing PTFE with up to 20 % by weight of CF, after which it slightly changes (Fig. 8). The error of our experiments did not exceed 6 %, the value of approximation accuracy for impact viscosity, the limit of strength at compression, and heat resistance by Wick, is respectively: 0.974, 0.970, 0.973.

Studying the impact of CF content on the strength characteristics of PCMs based on PTFE (Fig. 8) indicates that the optimal content of CF in the PCM is 20 % by weight. In particular, for the PCM with the specified filler content, the compression strength limit is almost 4 times higher than that of the original polymer (87 MPa).

Notable is the fact that the nature of change in the σ - ε curves for PTFE and PTFE-based PCMs is different (Fig. 9).

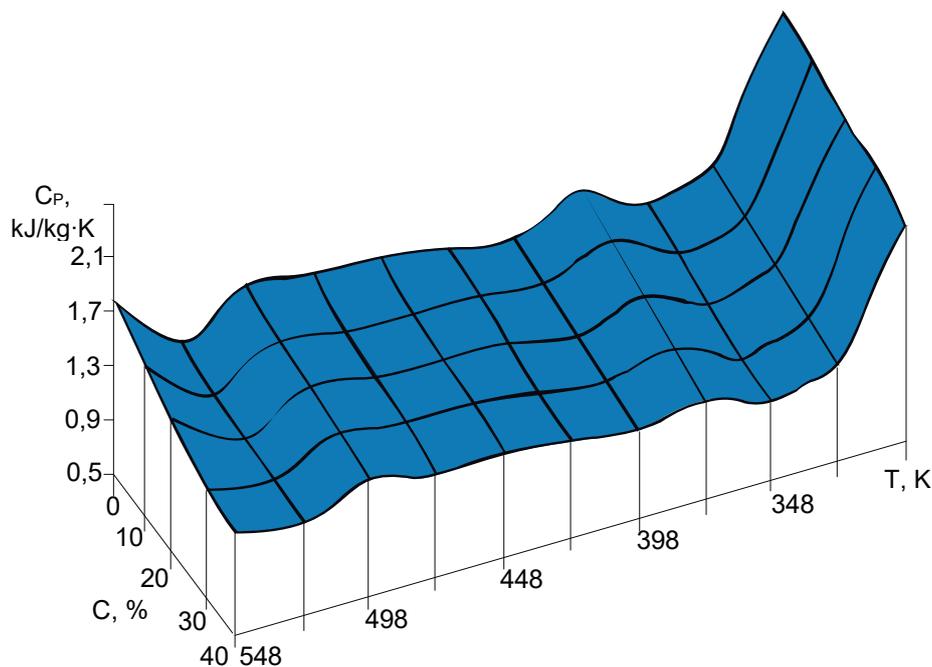


Fig. 7. Effect of the carbon fiber content on the specific heat capacity of polymeric-composite materials based on polytetrafluoroethylene: C – carbon fiber content, % by weight; T – temperature, K; C_p – specific heat capacity

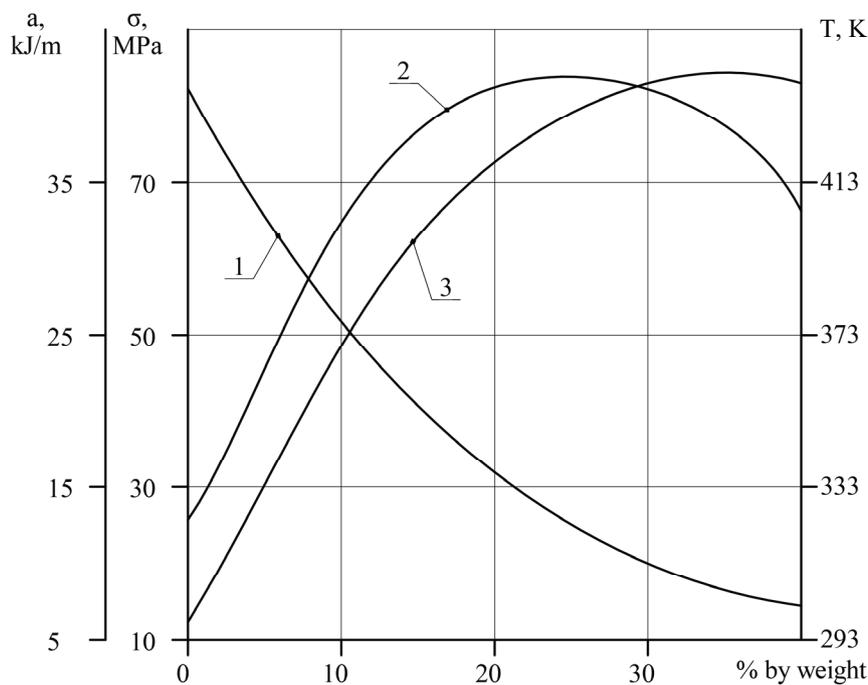


Fig. 8. Dependence of the physical-mechanical characteristics of polymer-composite materials based on polytetrafluoroethylene on the content (% by weight) of carbon fiber: 1 – impact viscosity; 2 – limit of strength at compression; 3 – heat resistance by Wick

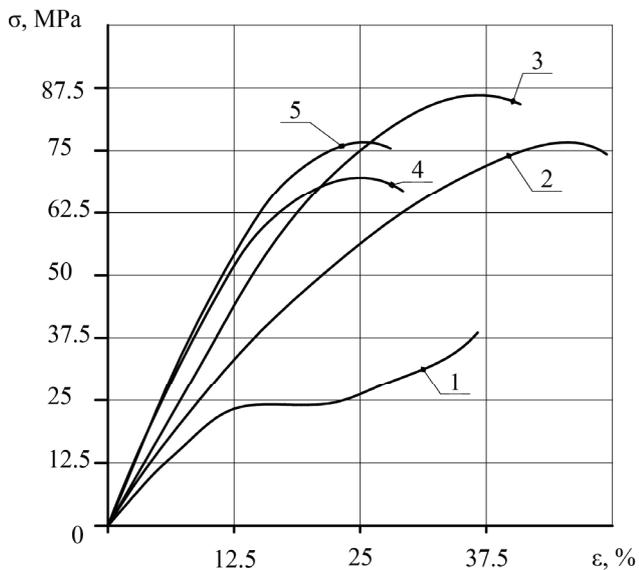


Fig. 9. Dependence of the strength limit and relative elongation at compression of the polymeric materials based on polytetrafluoroethylene on the carbon fiber content: 1 – polytetrafluoroethylene (without filling); 2 – 10 wt % carbon fiber; 3 – 20 wt % carbon fiber; 4 – 30 wt % carbon fiber; 5 – 40 wt % carbon fiber

We have investigated the influence of the nature of lubrication and testing modes on the tribotechnical characteristics of PCMs. The oil of grade MS-20 (GOST 21743-76) and drinking water (GOST 2874-82) were used as a lubricating/medium. In the case of oil lubrication (Fig. 10, a) in the pressure interval of 1...8 MPa,

there is a pattern opposite to that related to dry friction (with an increase in the slip rate, the friction coefficient increases). In the intervals from 10 to 14 MPa, the change in sliding speed does not affect the friction coefficient.

It should be noted that at slip speeds of 0.8 and 1.3 m/s, the friction coefficient increases with increasing pressure, while at 2.6 m/s it remains almost unchanged over the entire pressure range, and is 0.051...0.053.

When lubricated with water (Fig. 10, b), the pattern of curves has a different character. With an increase in pressure (4...8 MPa), the friction coefficient increases to a certain value after reaching which, it stabilizes. The friction coefficient at a decrease in the sliding speed and at lower pressure values is stable. This is due to favorable conditions for the formation of a transfer film on the counter-body. At the same time, the effect of changing the speed is similar to the dry friction process, with its increase, the friction coefficient decreases. Thus, at the maximum slip speed, it rises monotonously from

0.037 at a pressure of 1 MPa to 0.082 at 14 MPa, that is, it increases by more than 2 times. At a speed of 1.3 m/s, the friction coefficient increases sharply in the region from 1 to 8 MPa (up to 0.074), then stabilizes in the pressure interval from 8 to 12 MPa, after which it falls slightly. At a speed of 0.8 m/s, the friction coefficient increases sharply to a pressure of 4 MPa, reaching a value of 0.085. The stabilization region falls in the pressure range of 4–12 MPa. Here, the friction coefficient grows slightly (from 0.085 to 0.089) at 12 MPa, after which it falls slightly – to 0.082.

The results of studying the weight wear of PCMs are given in Table 7.

Table 7

Effect of operating modes on the weight wear of PCMs when lubricating with oil and water

Pressure, MPa	Speed, m/s					
	Oil			Water		
	0.8	1.3	2.6	0.8	1.3	2.6
1.0	+0.013	+0.045	+0.048	+0.025	+0.058	+0.067
2.0	+0.005	+0.046	+0.050	+0.02	+0.011	-0.011
4.0	+0.002	+0.039	+0.047	+0.03	+0.019	-0.012
6.0	0	+0.016	+0.06	+0.014	+0.019	-0.012
8.0	+0.012	+0.022	-0.025	+0.09	-0.004	+0.051
10.0	+0.024	+0.022	-	-0.012	-0.012	-0.044
12.0	-0.002	0	-	-0.017	-0.028	+0.018
14.0	-0.002	0	-	-0.02	-0.088	+0.007

Note: Table 7 gives data on changes in the sample weight in %

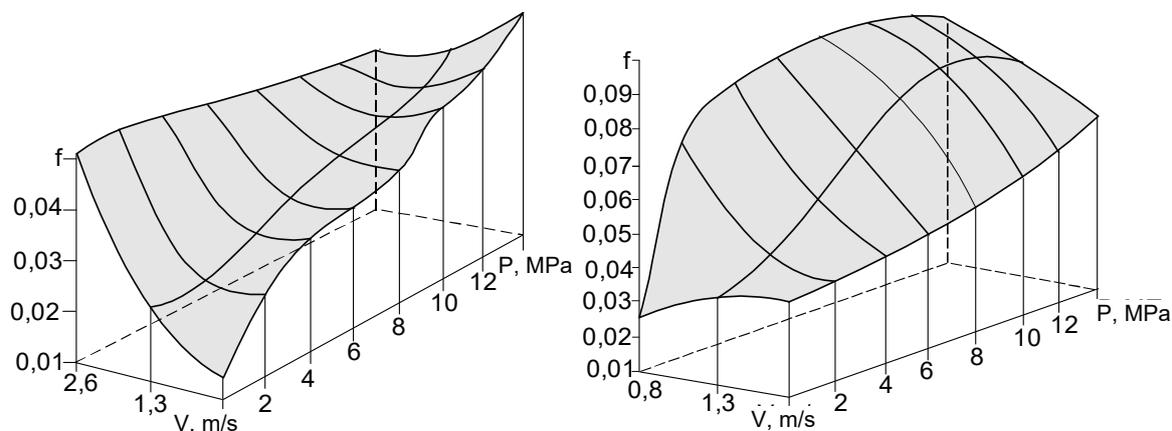


Fig. 10. Dependence of friction coefficient on the operating modes of the polymer-composite material based on polytetrafluoroethylene, reinforced with 20 % by weight of carbon fiber:
a – when lubricated with an oil; *b* – when lubricated with water

The study results have established (Table 7) that at low pressure (up to 6 MPa), the mass of almost all experimental samples increases, regardless of the slip rate. The only exceptions are working conditions for a tribological conjugation at a speed of 2.6 m/s in the case of lubricating with water.

6. Discussion of results of studying the characteristics and properties of polymeric-composite materials

When PCMs are filled with CFs at 10 and 20 % by weight (Fig. 3, *a, b*) the latter are arranged in the matrix evenly, without the formation of clusters. This is explained by the optimal ratio of the number of components of the polymer–CF system. With an increased CF content up to 30...40 % by weight, there begins the process of PCM stratification, zone 2 (Fig. 3, *c, d*). It can be explained based on the microphotographs shown in Fig. 3, *c, d*, and Fig. 4, *c, d*). In the case where CFs intersect, they are interlocked by friction forces. When compressed, the sample volume decreases, and the CF cluster loculi increase. It was established that the number of loculi and their volume (size) increases with an increase in the mass share of CF in the PCM. Loculi are formed in the process of pressing, that is, with a decrease in the physical volume of the sample. The available pressure (up to 40 MPa) is not enough for the PTFE to wrap the fibers that are in the loculi. As a result, when heated, the delamination process occurs, because the polymer is separated by fibers, and the temperature and pressure in the fiber accumulation places do not provide a monolithic structure of the resulting PCM. This process – intensive delamination – is fair when filling CFs at 30 and 40 % by weight due to their large physical quantity. Loculi in zone 1 (Fig. 4, *c, d, 5, b*) are formed in the direction that is perpendicular to pressing through the mechanism of ordering filamentous fillers at compression. This effect was noted [6], and, therefore, our results can supplement it.

The introduction of CF into the polymer matrix does not significantly affect the heat resistance of PCM. Some loss of its mass is registered when CFs are introduced in the amount of 10 % by weight; this is due to the loss of moisture and the burnout of CF modifiers. Subsequently, the effect of CF on heat resistance is insignificant.

Analysis of the temperature dependence of specific heat capacity, shown in Fig. 7, suggests that the descending areas of curves in the temperature region of up to $-50\text{ }^{\circ}\text{C}$ are due to the fact that below $19.6\text{ }^{\circ}\text{C}$ the elementary cell of the fluoroplastic-4 crystal consists of 13 groups of CF_2 , above $19.6\text{ }^{\circ}\text{C}$ – 15 groups of CF_2 . At $19.6\text{ }^{\circ}\text{C}$, the three-wedge arrangement changes to a less ordered, hexagonal one, which is accompanied by an increase in the volume of crystallites by $0.0058\text{ cm}^3/\text{g}$ (1.2 % by volume), or an increase in the volume of the sample at a degree of crystallinity of 68 % by 0.74 %. In the presence of external pressure, the transition point decreases by $0.013\text{ }^{\circ}\text{C}$ per atmosphere. At $30\text{ }^{\circ}\text{C}$, the second transition of the crystalline structure occurs but the change in volume is barely 1/10 of the volume change at $19.6\text{ }^{\circ}\text{C}$.

The nature of the curves (Fig. 7) in temperature intervals from 363 to 403 K can be identified as the transition of amorphous solid PTFE to supercooled liquid. In this region, the surface of the plot is descending. In the temperature range from 498 to 548 K, the melting of crystallites begins and the polymer transitions to an amorphous state. In general, it was established that with an increase in the content of CF from 10 to 40 % by weight in the studied temperature interval (298...523 K), the heat capacity decreases by 16...39 % compared to the binder.

A decrease in the impact viscosity (Fig. 8) with an increase in the amount of introduced CFs is caused by the fragile structure of CFs. Thus, the viscosity (elasticity) of the PCM decreases while its fragility increases. Indicators such as the compression strength limit and heat resistance by Wick increase when filled with CFs up to 20 % by weight and 30 % by weight, respectively. The filler contributes to both the reinforcing effect and increases heat resistance due to the fact that the CF is a heat-resistant component of the PCM. Upon reaching the specified filling parameters of 20 % by weight, the compression strength limit and heat resistance by Wick stabilize or begin to decrease due to the loss of reinforcing and heat-resistant effects. For such a large amount of fiber (30...40 % by weight), the binder is not enough to obtain a rational structure of the PCM.

Based on the above results in Fig. 9, curve 1 (PTFE without filling) belongs to the curves of type I. It has a straight section to the stress corresponding to the boundary of proportionality; the region where there is some deviation from the Hook law is associated with the manifestation of segmental

mobility of macromolecules. In addition, the yield strength is clearly visible, after which the plastic deformation and a stage of deformation strengthening and destruction develop. The PCM curves 2...5 in Fig. 9 belong to type II: in addition to the straight section describing elastic deformation at its small values, a parabolic section of the curve characterizing homogeneous plastic deformation is observed.

It was found by the study of weight wear of the samples (Table 7) that there is a progress of two competing processes. Namely, swelling, which leads to a weight gain of samples (by 0.007...0.067 % when lubricated with water, and by 0.002...0.05 % when oiled), and wear.

The limiting factor of the proposed method of mixing components of composite material is the inability to obtain a monolithic PCM, due to the delamination of the composition, at the stage of cold pressing, at a concentration of CF exceeding 30 % by weight. The disadvantages of our study include the absence of intermediate values of CF concentration in the ranges of 10...20 % by weight and 20...30 % by weight. In the future, it is necessary to perform detailed research on changing the characteristics and properties of PCMs based on PTFE and CFs with a smaller step (2.5...3 % by weight) varying the concentration of the filler.

Thus, it is possible to recommend the PCM, based on PTFE, reinforced with CF in the amount of 20 % by weight, for the tribological conjugations in machines and mechanisms that operate both under a dry friction mode and in a lubrication environment. In further studies in this area, it is necessary to pay attention to the impact of the duration of mixing and the value of the electromagnetic field on the quality of the distribution of the filler and its adhesion with the main material.

7. Conclusions

1. It was established that when carbon fibers are introduced into PTFE in the amount of 10 and 20 % by weight,

they are distributed evenly in the PCM. A further increase in the concentration of the filler (30 and 40 % by weight) leads to the PCM delamination. This is explained by the local clusters of CFs and an insufficient amount of the binder, which prevents the formation of a monolithic PCM when it is heated (baked).

2. It was established that compared to the starting polymer, the specific heat capacity of the composites reinforced with CFs in the amount of 10...40 % by weight decreases by 16...39 %. At the same time, the heat resistance by Wick and the compression strength limit increase by 60...140 °C and by 1.7...3.5 times, respectively. The characteristics and properties of the designed PCMs are not inferior to the well-known composite materials based on PTFE and CF, while the cost of their manufacture is much lower. The increase in heat resistance when filling with CFs is explained by the heat resistance of the filler. The increase in the compression strength limit brings about the effect of the reinforcement of the CF matrix of the starting material. When using the material lubricated with oil and water, the friction coefficient is reduced by 2...2.5 times and 4...7 times, respectively, compared to dry friction. The designed material should be operated at the following values of the PV performance criterion: under a dry friction mode, up to 4 MPa·m/s; at friction with lubrication, up to 36.4 MPa·m/s.

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