Досліджено вплив механохімічної активації матриці, наповнювачів різної природи і композиції на структуру та експлуатаційні властивості політетрафторетиленових композитів. Встановлено оптимальні режими процесу механічної активації матричного політетрафторетилену, волокнистих і дисперсних наповнювачів. Показано, що розроблені композити на основі політетрафторетилену з активованими інгредієнтами за рівнем міцності, зносостійкості і довговічності істотно перевищують аналоги

Ключові слова: політетрафторетилен, наповнювач різної природи, механічна активація, надмолекулярна структура, композит, довговічність

Исследовано влияние механохимической активации матрицы, наполнителей различной природы и композиции на структуру и эксплуатационные свойства политетрафторэтиленовых композитов. Установлены оптимальные режимы процесса механической активации матричного политетрафторэтилена, волокнистых и дисперсных наполнителей. Показано, что разработанные композиты на основе политетрафторэтилена с активированными ингредиентами по уровню прочности, износостойкости и долговечности существенно превышают аналоги

Ключевые слова: политетрафторэтилен, наполнитель различной природы, механическая активация, надмолекулярная структура, композит, долговечность

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DESIGNING AND EXAMINING POLYTETRAFLUOROETHYLENE COMPOSITES FOR TRIBOTECHNICAL PURPOSES WITH ACTIVATED INGREDIENTS

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1. Introduction

Wide application of polymer composite materials (PCM) based on polytetrafluoroethylene (PTFE) in the nodes of friction and compaction of all kinds of machines and equipment is due to specific features of its molecular structure and supermolecular structure (SMS), which provide for the implementation of unique combination of indices of deformation strength, tribotechnical, anticorrosive, thermo-physical and other operational characteristics [1].

Composites based on PTFE and modified fillers are successfully used as substitutes of traditional materials for tribological purpose. Dispersed and fibrous fillers, as well as ultra dispersed over recent years, are widely used [2].

Providing the optimal level of interaction of matrix polymer and fillers defines the structure and characteristics of boundary layers in a composite. They are complicated by specific structure of the molecular chain of PTFE, which causes pronounced chemical inertness to most solid-phase components of the composition and lack of the viscous-fluid state, which could contribute to wetting the surface layer of particles of a filler-modifier [3].

Practical implementation of this technology implies providing optimal structure of the inter-phase layer on the basis of a comprehensive analysis of specific features of morphology of the surface layers of particles-modifiers and their energy parameters of influence on the processes of adsorption and chemisorption interaction.

Thus, a question of examining the preparation of matrix and fillers and of developing the base for obtaining composite for tribological purposes based on PTFE is a relevant task of the technology of polymeric and composite materials that solves important technological task. A problem that determines technical and economic efficiency of applying new composite materials is the prediction of operating properties and selection of methods for achieving their necessary values, which requires appropriate research.

2. Literature analysis and problem statement

To obtain an efficient PTFE-composite, the above-mentioned factors need to be considered when choosing the composition of a filler, its dispersity, energy state of the surface layer [4] and technology for the activation of ingredients [5], methods of combining components when obtaining a composite material and technological methods for the formation of PTFE products (patents of Ukraine Nos. 40282, 40959, 40960, 41868, 42870).

The properties of composite materials, in addition to the correct choice of filler, are largely determined by the obtaining technology that determines the nature of interaction at the inter-phase boundary "matrix – filler" and defines the set of properties while forming the material [6].

Due to characteristic SMS of PTFE, the most common and effective methods of activating its particles are mechanochemical effect at the high-energy plants [7] and the modification with fillers [8].

Despite certain advances in research into mechanical activation effects on the structure and properties of PTFE and its composites [9], there are practically no data on the use of mechanical activation for the pre-treatment of PTFE matrix and fillers to enhance adhesion between them and to increase wear resistance of PTFE-composite.

A positive effect of filling PTFE for improving tribotechnical characteristics is caused by the attenuation of intermolecular bonds in a polymer, formation of the optimum structure of material, involvement of fillers in the process of friction as inhibitors, and increase in workability of the film of friction transfer [10].

Paper [11] demonstrated that the modification of amorphous-crystalline polymers by means of filling leads to changes in the character and morphology of SMS, and this is one of the main reasons for the transformation of properties of a composite.

The structurally active fillers which are distinguished by extremely small particle dimensions are the most interesting in terms of the impact on tribotechnical characteristics of PCM [12]. Their use ensures maximal structuring of polymer matrix at the different levels of structural organization and obtaining materials with unique properties.

Considering the aforementioned, it appears appropriate to study influence of the structure-creating processes during mechanochemical activation and in the presence of fillers of various nature on the structure and properties of PCM for tribotechnical purposes based on PTFE.

3. Aim and tasks of research

The aim of the work is the study of specific features of the mechanisms of structural organization in the course of modification of amorphous-crystalline PTFE with the energy methods of influence and fillers of various nature, as well as designing PTFE composites with improved operating characteristics on their basis.

To achieve the set goal, the following tasks were to be solved:

– to conduct a study of supermolecular structure of PTFE-composites and analysis of changes in the structural-phase state depending on the composition and properties of fillers;

– to perform comprehensive research into the properties of PCM based on PTFE in a wide range of concentrations of fillers and to identify patterns in their changes caused by the structural reorganization of matrix of composites and modifying factors of the technology of fillers;

– based on the generalization of results, obtained in the course of research, to receive an antifriction composite material based on PTFE with high physical and mechanical properties for the work under conditions of heavy wear.

4. Materials and methods of research into effect of the mechanical activation technology and fillers of various nature on the structure and properties of PTFE-composites

4. 1. Examined materials and equipment used in the experiment

The objects of research were powder-like industrial PTFE of the F-4 PN trademark (GOST 10007-80) and composites based on it.

As a fibrous filler, we used fragments of carbon fibers (CF), made from the carbon fabric UTM-8-1s (TU 48-20-17-77), obtained by the method of chemical treatment in the aqueous solution of fire retardants $Na_2B_4O_7{\cdot}10H_2O+(NH_4)_2HPO_4$ and annealing at temperature 723±20 K in the media of natural gas CH_4. Average diameter of the fragments of CF was 10–12 µm, average length after grinding was 100–150 µm.

Kaolin of the trademark KS-1 from the Prosyansky deposit (Dnipropetrovsk Region, Ukraine) was used as a dispersed phase. Prosyansky's kaolin with the content of 49,8–56,2 % by weight of finely dispersed particles of fractions <0,001 mm belong to the group of medium-dispersed ones, and by the total content of 88,1–89,6 % by weight of particles of fractions <0,01 mm – to the highly dispersed ones.

PTFE powder was prepared by the mechanical activation in the dry state in the high-speed mill MRP-1M at the rotation speed of working bodies of the mill $n=9000$ min^{-1} for $\tau=5$ min [13].

Mechanical activation of fillers was carried out in the high-speed mill MRP-1M under the following modes: for the fibrous fillers – at the rotation speed of working bodies $n=7000$ min^{-1} for 9 min.; for the dispersed fillers – at the rotation speed of working bodies $n=7000$ min^{-1} for 5 min.

Based on the experience of previous research [14], the mixing of ingredients of the compositions was carried out by a two-stage regime: mechanical activation of the matrix PTFE; mechanical activation of the filler under selected mode; introduction of activated PTFE to the activated filler (1:1 by mass) and their joint mixing ($n=7000$ min^{-1}, $\tau=5$ min); introduction of the rest of the formulation amount of activated PTFE and joint mixing ($n=7000$ min^{-1}, $\tau=5$ min).

Samples of the tested materials were obtained by the technology of cold pressing of composition (pressing pressure $P_{pr}=(50,0–70,0)$ MPa) followed by the slow sintering of tableted workpieces in the air at 365±5 °C at the rate of heating-cooling 40 °C/h.

4. 2. Methodology for determining the indices of properties of the samples

The methodology of examining the properties of composite included determining density ρ (kg/m^3), strength at break (destructive tension at destruction) σ_b (MPa), relative elongation at break δ (%) and wear intensity $I{\cdot}10^{-6}$ (mm^3/N·m) as the basic data about material, which determine its workability.

Testing for strength and relative elongation at break was carried out on the ring samples ø50×ø40, height 10 mm, using rigid semi-disks in accordance with GOST 25.603-82 at the tensile machine MP-05-1 at the rate of movement of grippers 10 mm/min and the load of 100 kgf.

Density ρ (kg/m^3) of the samples was determined by the method of hydrostatic weighing in accordance with GOST 15139-69.

A study of wear intensity was carried out at the standard friction machine 2070 SMT-1 according to the scheme "partial insertion – shaft" in accordance with GOST 11629-75.

A counter-body was a roller ø48 mm, made of the steel 45 (HRC 45, Ra – 0,72 μm). The partial insertion was made of the examined material and represented a sector 16 mm wide from the ring ø80×ø60 mm, height 9 mm.

The magnitude of wear of the samples was determined gravimetrically by analytical scales with accuracy to 10^{-5} grams and recalculated to wear intensity by the known methods [15]. When evaluating intensity of the PCM wear, a mean-square error was regulated by the errors in measurement of the sample's mass, velocity and duration of friction and did not exceed 5 %.

Temperature in the area of contact "PCM – steel counter-body" was determined by the professional infrared thermometer (pyrometer) CEM DT-8867H.

Structures of PTFE-composites with activated ingredients were explored through the high resolution scanning electronic microscope TESCAN MIRA 3 LMU.

Degree of crystallinity and parameters of the crystal lettuce of the designed composites were determined by using the radiographic method (diffractometer DRON-4-07), using the filtered Co Kα radiation (of wavelength 0,179 nm), focusing by Bragg-Brentano θ–2θ (2θ is the Bragg angle). Values of current and voltage in the X-ray tube were 20 mA and 40 kV. The sample images were taken under continuous registration mode (speed 1 °/min), the range of 2θ angles is from 10° to 55°.

Planning and processing of experimental data were performed by the methods of mathematical planning of experiment and mathematical statistics.

5. Results of research into the structure and properties of the designed PTFE-composites

Results of research into the effect of mechanical activation of matrix PTFE on the operational properties of PTFE-composites, filled with the CF fragments at different concentrations, are given in Table 1 [7].

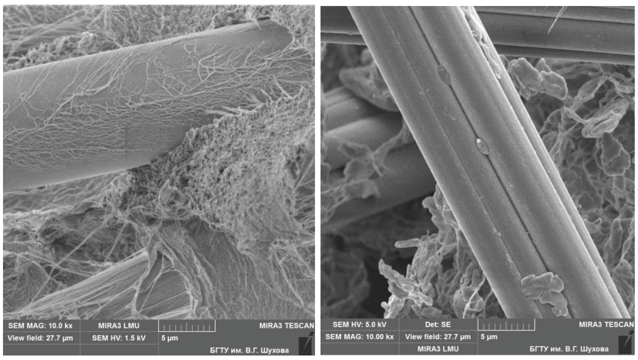
Table 1

Properties of PTFE-composites filled with the CF fragments depending on the mechanical activation of matrix and concentration of filler

Composition of composite	Density ρ, kg/m³	Strength at break σ_b, MPa	Relative elongation δ, %	Intensity of wear I, 10^{-6} mm³/N·m
90 % PTFE+ +10 % CF	2010	17,5	90	25–60
90 % PTFE*+ +10 % CF	2020	17,9	98	21–51
85 % PTFE+ +15 % CF	1980	18,3	105	20–50
85 % PTFE*+ +15 % CF	1990	19,1	115	17–42
80 % PTFE+ +20 % CF	1960	20,4	120	19–45
80 % PTFE*+ +20 % CF	1980	22,1	145	16–38
75 % PTFE+ +25 % CF	1950	16,9	115	18–40
75 % PTFE*+ +25 % CF	1960	18,4	125	15–34

*Note: * – mechanically activated PTFE*

Electronic microscopic studies of the structure of PTFE-composites, filled with the CF fragments, with the activated and non-activated matrix are displayed in Fig. 1.



a *b*

Fig. 1. Micrographs of structures of the PTFE-composites filled with the CF fragments, based on: *a* – activated matrix; *b* – non-activated matrix

As a result of the mechanic activation effect, the modification of the surface layer of the CF fragments, activated by PTFE (Fig. 1, *a*) occurs, the PTFE particles are distributed on the surface of CF with higher uniformity, which provides for an increase in their activity in the processes of interaction with matrix PTFE during the formation of the composite. The fragments of CF, coming into contact with the activated particles of PTFE, form primary adhesion bonds, reducing structural defectiveness of the composition and probability of defects occurrence in the course of formation of the composite.

Results of studying the influence of mechanical activation of matrix PTFE on the operational properties of PTFE-composites, filled with kaolin in different concentrations, are given in Table 2 [16].

Table 2

Properties of PTFE-composites, filled with kaolin, depending on the mechanical activation of matrix and concentration of filler

Composition of composite	Density ρ, kg/m³	Strength at break σ_b, MPa	Relative elongation δ, %	Intensity of wear I·10^{-6}, mm³/N·m
98 % PTFE+ +2 % kaolin	2190	15,0	350	11,95
98 % PTFE*+ +2 % kaolin	2180	16,6	409	10,80
98 % PTFE+ +4 % kaolin	2180	12,1	295	12,50
98 % PTFE*+ + 4 % kaolin	2170	12,3	315	11,75
98 % PTFE+ + 6 % kaolin	2170	13,5	420	13,45
98 % PTFE*+ + 6 % kaolin	2160	13,8	445	12,95

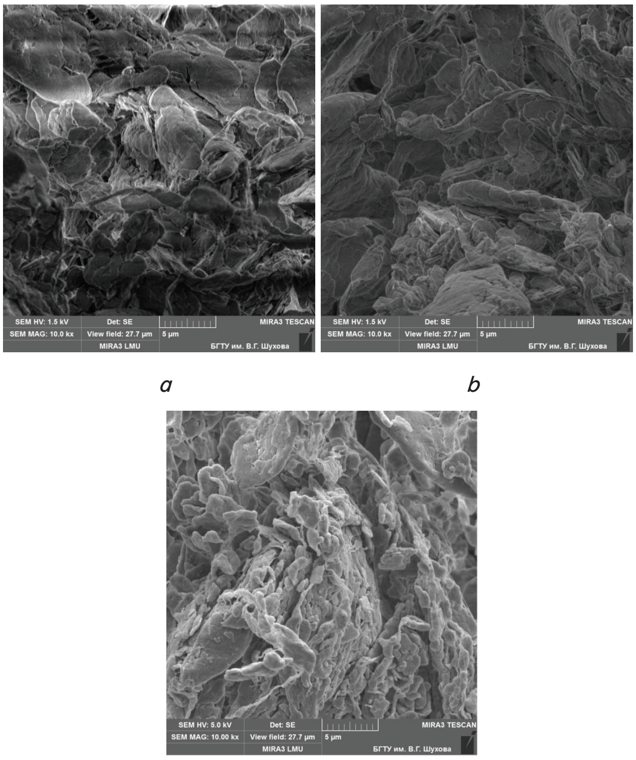
*Note: * – mechanically activated PTFE*

Electronic microscopic studies of the structure of PTFE-composites, filled with kaolin in different concentrations, are displayed in Fig. 2.

In the micrographs, the particles of kaolin and super-molecular formation of the activated matrix, the nature of which depends on the concentration of filler, are identified. Within the entire concentration range of filling, these composites have a typical structure, similar to the structure of pure PTFE, but more porous (Fig. 2, *a*).

When increasing the concentration of the filler, SMS of the matrix becomes more fluffy and defective; the quantity of micro cavities increases (Fig. 2, *b*); individual particles of kaolin, which are separated from the matrix by micro-cracks along the entire surface of the particle, are observed.

An increase in the concentration of the filler leads to the aggregation of kaolin particles. These changes are manifested particularly vividly at the concentrations of geo-modifier higher than 6 % by weight (Fig. 2, *c*).



a *b*

c

Fig. 2. Microstructure of PTFE-composite with kaolin at its content (% by weight): *a* — 2; *b* — 4; *c* — 6

A synergistic effect of the use of mechanical activation of both matrix and PTFE fillers before their mixing was expressed by the increase in the indices of operational characteristics of the obtained composites (Table 3).

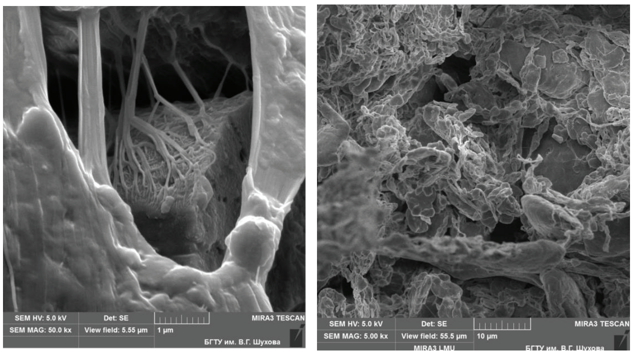
Table 3

Properties of composites based on the activated PTFE depending on the mechanical activation of fillers

Composition of composite	Density ρ, kg/m³	Strength at break σ_b, MPa	Relative elongation δ, %	Intensity of wear I, 10^{-6} mm³/N·m
80 % PTFE+ +20 % CF	1980	22,1	145	16,0–38,0
80 % PTFE+ +20 % CF*	1990	24,2	154	3,5–6,5
98 % PTFE+ +2 % kaolin	2180	16,6	409	10,8
98 % PTFE+ +2 % kaolin*	2170	17,8	432	6,9–9,3

*Note: * – mechanically activated PTFE*

The structures of such PTFE-composites with the activated fillers of various nature were explored by the methods of electronic microscopy (Fig. 3).



a *b*

Fig. 3. Microstructure of composite based on the activated PTFE, filled with an activated filler:
a — with fragments of CF, *b* — with kaolin

A synergistic effect of the use of mechanical activation of the matrix, fillers, their mixing under a two-stage mode, and the use of binary filler of various nature, was expressed by a significant increase in wear resistance while the required values of physical and mechanical properties of the developed PTFE-composites were preserved (Table 4).

Table 4

Physical, mechanical, and tribotechnical properties of the developed activated PTFE-composites with binary filler

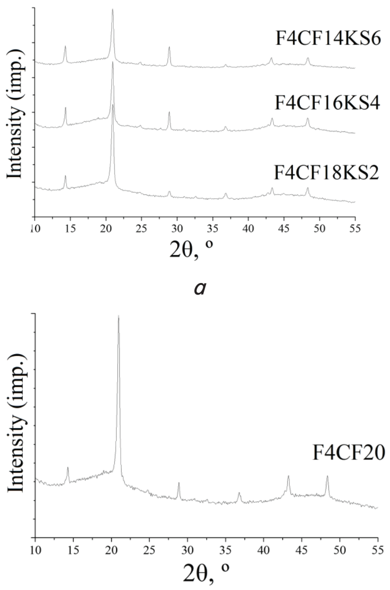
Composition of composite	Density ρ, kg/m³	Strength at breakage σ_b, MPa	Relative elongation δ, %	Intensity of wear I, 10^{-6} mm³/N·m	Friction coefficient
PTFE+ +18 % CF+ +2 % kaolin	2084	10,7	115	1,25	0,25
PTFE+ +16 % CF+ +4 % kaolin	2106	12,9	120	1,15	0,24
PTFE+ +14 % CF+ +6 % kaolin	2213	18,7	125	0,85	0,24
PTFE+ +20 % CF (control)	1907	24,2	154	3,5-6,5	0,26

An application of X-rayed structural analysis made it possible to obtain information on the structural organization of PTFE and the effect of fillers of various nature on it, which is important for the antifriction PTFE-composites.

The research demonstrated that the introduction of binary filler causes a significant change in the degree of crystallinity and all the parameters of supermolecular structure of PTFE (Table 5).

Fig. 4 presents diffractograms of the PTFE-composites with binary and fibrous filler.

Results of studying the effect of temperature of the friction surface of the system "PTFE-composite – counter body" depending on the concentration of filler and the duration of wear testing are presented in Fig. 5.



a

b

Fig. 4. Diffraction activated PTFE-composites filled: *a* – BB+kaolin (at different concentrations); *b* – 20 wt. BB %

Table 5

Dimensions of crystallites by Scherrer and degree of crystallinity of the developed PTFE-composites

Peaks	d, Å*	7,19	4,9	3,6	2,835	2,455	2,423	2,184	DC
	2θ, º	14,3	21,0	28,9	36,8	42,7	43,3	48,3	
PTFE+ +18 % CF+ +2 % kaolin		45,8	27,4	35,2	32,5	38,2	41,1	37,1	0,392
PTFE+ +16 % CF+ +4 % kaolin		44,2	28,8	47,5	31,8	56,1	37,0	36,7	0,347
PTFE+ +14 % CF+ +6 % kaolin		36,0	28,1	39,2	41,3	–	36,7	36,9	0,480
PTFE+20 % CF		40,0	29,6	51,2	31,4	64,7	40,3	44,6	0,406

*Note: * – interplanar distance*

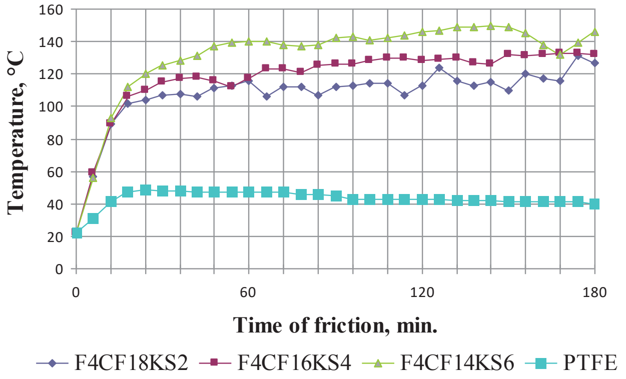
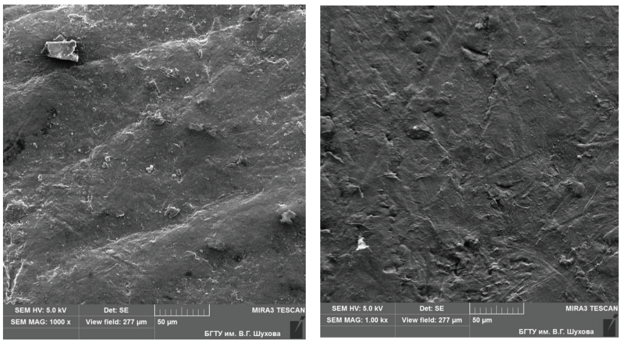


Fig. 5. Dependence of temperature of friction surface of the system "PTFE-composite – counter body" on the duration of wear testing depending on the concentration of the introduced fillers

Microstructures of the friction surface of the PTFE-composites with activated fillers of various nature were explored by the methods of electronic microscopy (Fig. 6).



a *b*

Fig. 6. Microstructures of friction surface of the PTFE-composite, filled: *a* – with 14 % by weight of CF+6 % by weight of kaolin; *b* – 20 % by weight of CF

A comparative characteristic of the developed composites for tribotechnical purposes based on PTFE with improved set of operational characteristics to the composites of existing brands is presented in Table 6.

Table 6

Comparative characteristic of the developed PTFE-composites for tribotechnical purposes

Index	Composites			
	F4CF20[1]	F4CF20[2]	F4CF20[3]	F4CF14KS6
Density ρ, kg/m³	1840	1980	1990	2213
Strength at break σ_b, MPa	14,0	22,1	24,2	18,7
Relative elongation δ, %	125	145	154	125
Intensity of wear I, 10^{-6} mm³/N·m	5,10	16,00	3,50	0,85
Friction coefficient for the steel 45	0,29	0,28	0,26	0,24

Note: 1. TU 301-05-16-89. 2. Mechanical activation of PTFE only. 3. Mechanical activation of both PTFE and CF

It follows from the analysis of Table 6 that the developed technology for obtaining antifriction PTFE-composite of a new generation allowed increasing wear resistance of the materials by 3,7–6,0 times, strength at break – by 1,4 times compared with materials of the old generation (TU 301-05-16-89).

6. Discussion of results of research into effect of the mechanical activation technology and fillers of various nature on the structure and properties of PTFE-composites

An analysis of Table 1 demonstrated that the optimal concentration of the CF fragments in a composite is 20 % by weight, which corresponds to the formation of more homogenous structure of the composite and high physical, mechanical and tribotechnical properties.

Using a mechanically activated PTFE-matrix improves the properties of PTFE-composites filled with fragments of CF:

strength at break – by (2,3–8,9) %, relative elongation – by (8,7–20,8) %, durability – by (15–16) % compared to the composites based on non-activated PTFE.

As can be seen from Table 2, polymer does not interact with kaolin in a mechanochemical way, that is, components in the composite "PTFE-kaolin" are not linked by chemical bonds. This connection is most likely to emerge due to the Van der Waals forces, which allows obtaining composites with the required physical and mechanical properties. Low values of operational properties of the PTFE composite with kaolin are the result of rather low adhesive capacity of the filler and obviously require additional technological techniques for its increase, including technological methods of energy influence both in the process of preparation of ingredients and while obtaining the composition.

In the process of energy influence on the ingredients of the composition, as a result of a separate mechanical activation of ingredients before their mixing, there is an increase in free surface energy, dispergation and change in their form. Mechanical load leads to the occurrence of metastable states of the surface layers. All these phenomena cause the appearance of particles of the fillers of uncompensated valences on the surface, contributing to the interaction of the particles of the filler with the matrix, to the initiation of reaction of polymerization of monomers or the formation of chemical bonds with polymer radicals. Simultaneously with the processes of activation of fillers, there is mechanochemical destruction of the PTFE macromolecules with the formation of radical fragments. The existence of active surface of the particles of fillers, on the one hand, and of a free radical of a macromolecule of polymer, on the other hand, may initiate the reaction of attachment of polymer to the filler.

With the help of the methods of electronic microscopy, we established the formation of a stable intermediate PTFE layer on the surface of fillers, which "heals" surface defects of fillers and contributes to the formation of a stable space cluster of the filler in the volume of the matrix of the composition (Fig. 3, *a*), which allows reaching maximal reinforcing effect and, thereby, improving strength characteristics of the composite and its wear resistance.

Mechanical activation of kaolin leads to an increase in the value of uncompensated charge of mineral particles, predetermined by specific features of crystalline and chemical structure of geomodifiers. As a result, we observed the effect of the oriented action of particles of the filler, which, acting as nuclei of crystallization, form spherulitic SMS of PTFE (Fig. 3, *b*).

An analysis of Table 3 demonstrated that mechanical activation of both the matrix and the filler of various nature, contributes to a considerable increase in the indices of PTFE-composites:

– in the process of filling with 20 % by weight of CF, strength at break increases by 9,5 % and 18,6 %, relative elongation – by 6,2 % and 28 %, wear resistance increases by 4.6–5.8 times and by 5,4–6.9 times compared to the non-activated CF and non-activated PTFE, respectively;

– in the composite with 2 % by weight of kaolin, strength at break increases by 7,8 % and 19,3 %, relative elongation – by 5,6 % and 23,4 %, wear resistance increases by 1,6 times and by 1,7 times in comparison to the non-activated kaolin and non–activated PTFE respectively.

As a result of mechanical activation of binary filler of the composites based on PTFE, materials underwent the following processes:

– grinding of PTFE to the ultra dispersed state, mechanodestruction of polymer with the formation of active polymer radicals;

– grinding of the complex filler with the formation of active centers at their surface;

– recombination of the formed radicals with active centers at the surface of the complex filler;

– homogenization of the mixture.

An analysis of Table 4 revealed that the best indices of operational properties are observed at the following concentrations of ingredients: 14 % of CF, 6 % of kaolin, the rest is PTFE.

Results of X-rayed structural studies demonstrated that during the introduction of binary filler to the matrix, there is a process of self-organization of the three-component system (matrix+fiber+kaolin) under conditions of mechanical activation of its ingredients and sintering of the pressed composition above melting temperature of the crystalline phase. As a result of this, amorphous crystalline SMS with decreased dimensions of crystallites is formed (Table 5).

It was established that the concentration dependence of the degree of crystallinity (DC) of PTFE-composites with binary filler has a complicated character: when increasing the filling with kaolin from 2 to 4 % by weight (at the decrease in the content of CF from 18 to 16 % weight, respectively), there is a linear decrease in the degree of crystallinity. Filling with 6 % by weight of kaolin and 14 % by weight of CF increases the degree of crystallinity (DC=0,480).

Information about structure of the PTFE-matrix of materials is contained in the range of the Bragg angles of reflection $2\theta=10-30°$: two halos are caused by the amorphous phase and reflex at $2\theta=21°$ is caused by the existence of the crystalline phase. The existence of a halo indicates that the amorphous phase of the matrix scatters X-rays not diffusively as a totally unordered system, but rather according to the existence of a "distant" order in it. The amorphous component of such a matrix can be characterized by the mean interplanar distance d. The particles of kaolin are located mainly in the amorphous areas of matrix PTFE, as is evident from the results of comparison of diffractograms (Fig. 4).

On the whole, the study of SMS-filled materials based on PTFE demonstrated that in it, similar to pure PTFE, a layer arrangement of PTFE molecules is preserved at the optimal concentration of fillers in the amorphous phase. This indicates that at a certain level of influence of external energy influence, the crystalline phase of PTFE, while passing into the amorphous one, self-organizes into a new, relatively ordered structure. This proves the reasonable expediency of the use of the filled PTFE in the nodes of friction of compressor equipment.

To assess the influence of fillers of various nature on the processes of friction and wear of PTFE composites, we carried out studies of the influence of temperature of surface friction of the system "PTFE-composite – counter body" depending on the concentration of filler and the duration of wear testing (Fig. 5). Testing was carried out under critical modes of friction without cooling in order to establish maximal workability of the developed composites.

An analysis of Fig. 5 reveals that the activated non-filled PTFE wears out evenly over the entire time interval in a relatively low temperature range (40–50 °C). When the composites filled with CF and kaolin were tested for wear, it was observed that the tribosystem is in the unbalanced state throughout the entire testing process; with an increase in the concentration of kaolin from 2 to 6 % by weight, intensity of wear decreases with an increase in temperature (from 100 to 150 °C).

Thus, temperature during PTFE-composites wear plays a double role. On the one hand, with an increase in temperature in the friction area, energy of thermal fluctuations increases, which should help to increase the intensity of wear. On the other hand, an increase in temperature attenuates the influence of load on the energy barrier of thermodestruction, thereby increasing it. Since the overall intensity of wear decreases with an increase in temperature, it is obvious that the second mechanism of the influence of temperature on the wear of PTFE-composites prevails.

The studies and analysis of micrographs of friction surfaces displays (Fig. 6) that in case of wear of the composite with CF (Fig. 6, *a*), the traces of wear are deeper, the furrows of weakening of the material are observed, which is not observed while wear of the composite with binary filling (Fig. 6, *b*), which promotes the increase in wear resistance by 4 times.

The rings of the compressor 4GM 2,5 U-3,4/2,8-251, made of the composite F4CF14KS6, allowed increasing working resource of the equipment of compressor engineering by 1,8–2,3 times.

7. Conclusions

1. It was established that a determining factor of increasing a set of operational properties of PTFE-composites with activated ingredients is the formation of spherulitic SMS of composites under the influence of active particles of dispersed filler that perform the role of nuclei of crystallization. Such spherulitic structures of PTF-composites counteract the development of micro-cracks, acting as the nodes that connect sections of the chains of PTFE macromolecules, thereby increasing the rigidity of PCM. Using the methods of electron microscopy, we established the formation of a stable intermediate layer of PTFE on the surface of a fibrous filler that “heals” surface defects of a filler and contributes to the formation of a stable space cluster of a filler in the volume of the matrix of composition, which allows reaching maximal reinforcing effect and, thereby, improving the strength characteristics of the composite and its wear resistance.

2. Comprehensive research into operational properties of the PTFE-composites with activated ingredients demonstrated that simultaneous introduction of the activated binary filler made it possible to considerably increase wear resistance of the material while maintaining high values of physical and mechanical properties. For each type of fillers, we determined optimal concentration, which ensures the creation of more homogenous structure of the composite and high physical, mechanical and tribotechnical properties. As a result of the conducted research, the prospects are outlined of using mechanical activation both for the PTFE matrix and for the fillers of various nature for improving operational properties of the composites.

3. Developed technological foundation for obtaining and structural modification of PTFE-composites made it possible to receive an antifriction composite material based on PTFE with high physical and mechanical properties for the work under conditions of heavy wear. Effective concentration of fillers in the matrix (CF – 14 % by weight, kaolin – 6 % by weight, the rest is PTFE) was determined, which corresponds to the highest value of properties of the composite. The rings of the compressor 4GM 2,5 U-3,4/2,8-251, made of the composite F4CF14KS6, allowed increasing working resource of equipment of compressor engineering by 1,8–2,3 times.

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