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Investigation of Operational Properties of Heterocomposite Materials for Application in Real-World Conditions

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ABSTRACT: Today, in the cotton industry, special attention is being paid to increasing the operational reliability of parts and structures in constant contact with cotton fibers and extending their service life. This article analyzes the modern materials used in the production of spikes for the loosening drum in the process of cleaning cotton fibers from small impurities in the cotton industry, as well as the work carried out to date on measures to improve the designs of these parts. Additionally, to reduce the actual contact surface of the loosening drum spike with cotton fibers and prevent damage to cotton fibers, the coating of the spike's working surface with new composite multifunctional polymer materials is considered in detail, along with the metallographic properties, mechanical and tribotechnical characteristics of these materials. Based on the conducted research, a wear-resistant polymer composite coating based on reactoplast with high operational reliability has been proposed.

KEYWORDS: wear-resistant, thermoset material, coating, fiber, drum peg, mechanical strength, tribological properties, morphological analysis, filler, reinforcing

I. INTRODUCTION

It is well known that the modern machine-building industry, like all sectors, is consistently developing day by day. Consequently, ensuring the necessary operational reliability and efficiency of machines and mechanisms, including technological equipment used in the cotton industry, is considered one of the most important factors today [1]. Therefore, in ensuring the operational reliability of cotton primary processing machines, the targeted use of highly effective composite polymer materials, as well as increasing productivity through the application of new multifunctional materials on the working surfaces of technological equipment, is one of the urgent scientific and technical problems awaiting solution [2]. Currently, there are various technological and structural methods for protecting cotton from mechanical damage. One of the most effective methods is the use of composite polymer materials on the parts and working surfaces of equipment that come into contact with cotton [3].

Numerous scientific and practical studies have been conducted by domestic and foreign scientists on improving the loosening drum of machines for cleaning fibrous materials. In particular, although certain positive results have been achieved in the cleaning process through the development of a spiked drum with elastic elements for cotton cleaning machines to remove small impurities, and through improving methods for calculating operating modes and parameters, insufficient research has been conducted on enhancing the spike material, which is the main technological working part of the fibrous material loosening drum, and on increasing productivity [4].

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The drum for loosening and cleaning raw cotton allows for cleaning the fiber from small impurities, separating them, and obtaining high-quality cotton fiber. The loosening drum consists of longitudinal rows fixed to a cylindrical rim, with spikes attached in each row, the ends of which form a sinusoid. These spikes are positioned at an angle in the radial plane corresponding to each row, which helps to improve and accelerate the process of cleaning cotton from small impurities. In this case, the seed cotton entering the drum is caught by spikes with a curved surface and is dragged along the mesh surface; the spike head effectively engages the cotton fibers due to its curved surface and the curved surface of the drum. The spikes, which form the working surface of the drum, are made of a multifunctional heterocomposite material resistant to impact and wear. Consequently, due to low friction between the cotton fiber and the spike, less fiber is retained on the spike surface. This ensures the cotton moves along the mesh surface in the desired direction. This allows for a reduction in the stoppage of cotton particles in the cleaning zone, which reduces damage, especially to high-grade cotton [5-6].

Fig1. General view of a metal carding drum

Figure 1 analyzes the modernization of the spikes on the loosening drum of a fibrous material cleaner made of metal, specifically by coating them with a heterocomposite polymer material. This approach aims to reduce damage to cotton fiber and seeds, as well as extend the service life of the working surfaces of the technological equipment [7].

However, although numerous research studies have been conducted on the damage to cotton fiber and seeds during mechanical collisions with metal spikes, there is a need for further investigation into the structure of the cotton cleaning loosening drum's spikes and their optimization using polymer composite materials. Such research could lead to a reduction in damage and an increase in operational efficiency.

II. MATERIALS AND METHODS.

A. Materials

In the cotton industry, the selection of ED-20 epoxy resin as a binder for coating the actual contact surfaces of cotton gin saw teeth with wear-resistant coatings is explained by its sufficient physical and mechanical properties and high adhesion strength to steel surfaces. ED-20 epoxy resin is an oligomer which, in the presence of the curing agent polyethylenpolyamine (PEPA), forms a reactoplast resistant to abrasive wear and corrosion. In various fields of mechanical engineering, particularly on the working surfaces or parts of technological equipment for primary cotton processing, the use of ED-20 epoxy resin as a binder provides numerous advantages to parts and structures, including high density, moisture/water resistance, resistance to highly aggressive liquid and gas chemical environments, resistance to mechanical forces, high corrosion resistance, thermal resistance, ability to function even at low temperatures, good adhesion to metal surfaces, ease of use, environmental safety, and several other benefits [8].

The properties of composite materials are improved by adding various types of dispersed and fibrous fillers to their composition [9]. The purpose of using dispersed fillers in polymer composite materials is to enhance the physical and mechanical properties of the material, increase their operational characteristics, and, additionally, reduce the cost of the material. Fibrous fillers increase the deformation properties of polymer materials. In this research work, silk processing waste was used as a fibrous filler. Since silk processing waste is a secondary raw material of the cotton industry, using it as a filler in the production of composite materials leads to a significant decrease in the cost of materials. Moreover, these

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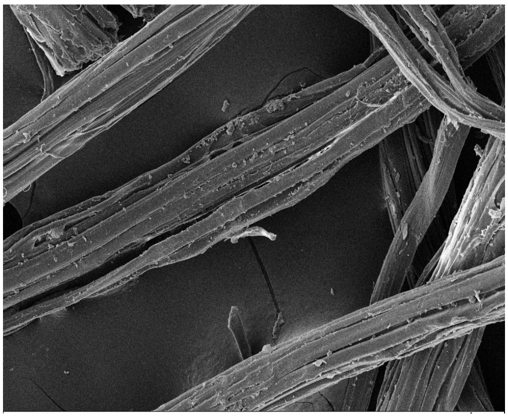
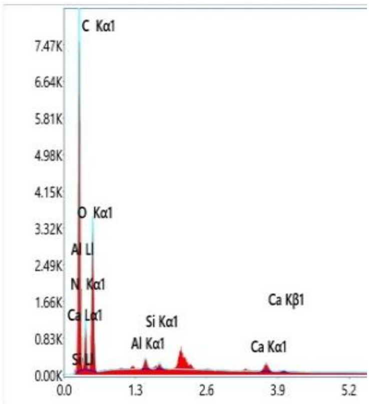
fibers are superior to other types of fibers as they absorb the binder well and do not form brittle structures on the fiber surface or at the boundary with the binder. Morphological analysis (Fig. 2, a) showed that the roughness of the fiber surfaces and the permeability of the binder ensure the strength of the composite material. In the X-ray diffractometer analysis of silk waste [10] used as reinforcement in the production of a polymer composite coating, C Kα1 and Si Kα1 represent X-ray lines characteristic of carbon, silicon, and aluminum, respectively (Fig. 2, b). These elements correspond to the natural composition of silk, as silk is mainly composed of proteins containing carbon, nitrogen, oxygen, and silicon. Additionally, elements such as Al Kα1, Ca Kα1, and Ca Kβ1 are present in the analysis, which are not typically found in silk. The presence of these elements may be due to their introduction into the silk processing waste from the external environment during processing. Kα1 is a characteristic X-ray line formed during the transition of electrons in an atom, and its highest value for C indicates that there are more carbon atoms in the composition of silk processing waste compared to atoms of other elements. This, in turn, can potentially increase the service life of parts operating under friction and wear conditions.



a



b

Fig2. Microstructure (a) and compositional analysis (b) of short-fiber silk processing waste obtained using a Gemini 500 (FE-SEM) scanning electron microscope

The role of disperse fillers in the production of wear-resistant coatings from organomineral polymer composite materials is invaluable. When added to composite materials as a dispersed filler, kaolin has the property of increasing their heat resistance, hardness, and wear resistance. Below is a morphological (Fig. 3, a) and compositional (Fig. 3, b) analysis of the AKF-78 grade of kaolin produced at the "Angren Kaolin" LLC enterprise in the city of Angren.

Due to the fact that the structure [11] of AKF-78, added as a disperse filler (Fig. 3, a), is plate-shaped and this structure is similar to the structure of graphite (Fig. 4, a), which is added to the composite material to ensure wear resistance properties, AKF-78 and graphite form a heterosystem, and this system minimizes cotton damage.

In the X-ray diffractometer analysis of AKF-78 Angren kaolin, shown in Fig. 3,b, the abscissa axis shows the energy expended by X-rays to fill the gaps between the atoms of the elements in the kaolin composition, corresponding to each element type. The ordinate axis shows the intensity of these X-rays, and higher intensity indicates a greater quantitative abundance of that element in kaolin. In this graph, the Al Kα1 and Si Kα1 peaks are the most intense, which is explained by the fact that they constitute the main part of kaolin. Smaller peaks for Mg Kα1, Ca Kα1, Cl Kα1 and Zn Lα1 indicate secondary elements or trace elements. The presence of Mg, Ca, Cl, and Zn in Angren kaolin indicates the presence of impurities or secondary minerals in the mineral composition.

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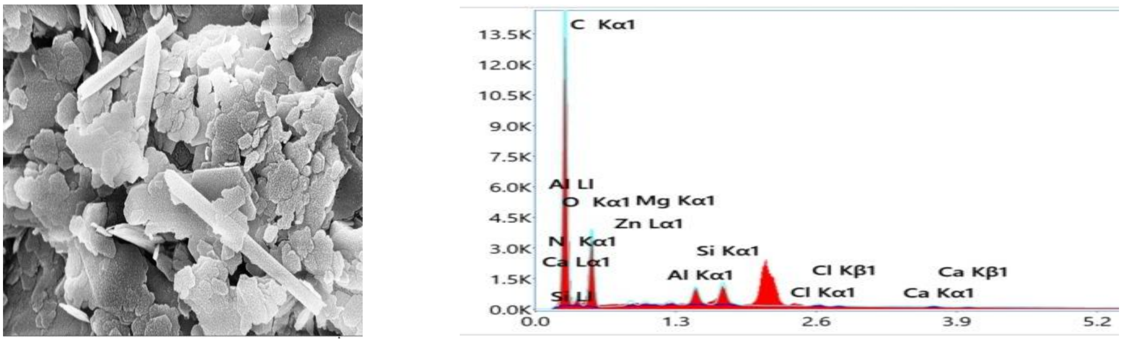

a b

Fig3. Microstructure (a) and compositional analysis (b) of AKF-78 kaolin obtained using a Gemini 500 (FE-SEM) scanning electron microscope (x100 magnification).

Graphite was selected for technological equipment used in primary cotton processing to reduce the formation of electrostatic charge resulting from frictional interaction between dispersed fillers, cotton, and polymer composite materials. It also aims to improve electrical and thermal conductivity in polymer composite materials. Graphite is essentially pure carbon with high thermal and electrical conductivity. Therefore, adding graphite to the composition of polymer composite materials can increase their thermal and electrical conductivity.

Mechanical activation of graphite particles prevents the removal of various moisture and oil layers formed on particle surfaces due to external factors, thus resisting the formation of a brittle structure at the interface between the matrix material and particles. Furthermore, as a result of activation, graphite particles form a layered structure similar to other dispersed fillers (Fig. 3, a), as shown in Fig. 4. This ensures an orderly and uniform distribution of fillers within the composite material

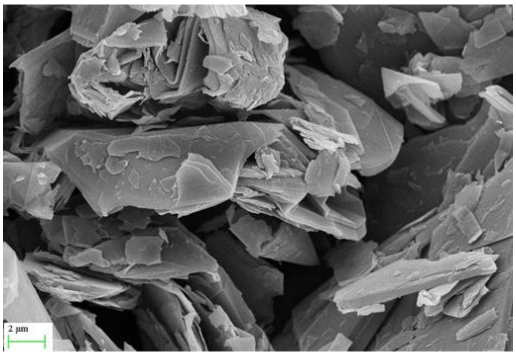

Fig4. Structure of mechanically activated graphite obtained using a Gemini 500 (FE-SEM) scanning electron microscope.

B. Methods

Method for determining hardness.

The determination of hardness for wear-resistant polymer heterocomposite materials was carried out according to the GOST 27326-87 standard, designed for determining the hardness of decorative coatings. The primary principle of the method is that it is performed by measuring the width of the impression left by a diamond needle with a sclerometer tip angle of (45±10) ° on the surface of the material under load [12].

Compositional analysis of materials. A high-precision diffractometer called Smart Lab X-RAY was used to determine the crystalline structure of materials, phase composition, the number and volume of crystal grains, and the density of particle distribution in the material. With these diffractometers, it is possible to study the process of structural formation of materials with high accuracy.

Structural analysis. For structural studies of fillers obtained by mechanical activation, a Gemini 500 (FE-SEM) emission scanning electron microscope was used. The Gemini 500 (FE-SEM) emission scanning electron microscope is a high-

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precision device that allows for the study of nanoscale particles. Such devices provide excellent pixel count and image quality at both high and low accelerating voltages.

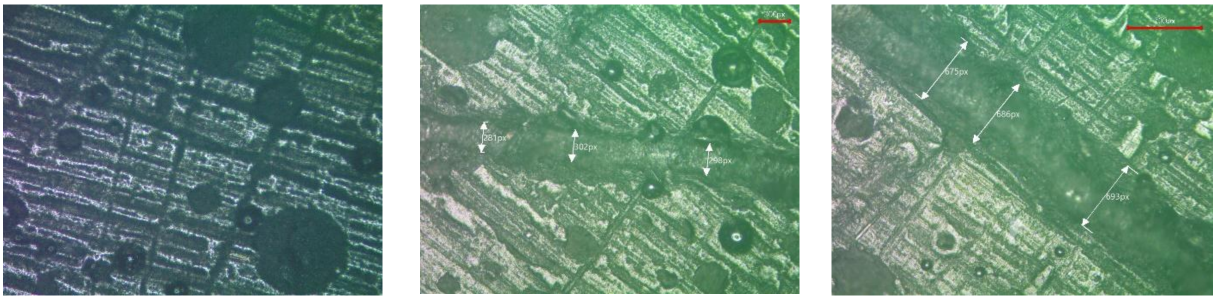
Study of Tribology. To examine the tribological properties of the samples, a rotary and reciprocating device of the "AT-900" brand, based on the "ball-disk" (finger-disk) method, was used to determine the friction and wear resistance of materials.

III. RESULTS AND DISCUSSION.

A. Hardness determination

One of the main factors ensuring the effective performance of heterocomposite materials based on thermosetting plastics under friction or abrasive wear conditions is their hardness. There are several methods for determining the hardness of samples, and in this study, the method of determining hardness by scratching the sample surface was used.

The scratching method of determining hardness is carried out by scratching the sample surface with a diamond or other non-deformable indenter under constant load. This method is not standardized, and in practice, various hardness criteria (Hc) determined by scratching are used. In this study, the magnitude of the load (P) required to produce scratch marks with a width of 50 μm was determined. A diamond cone with a 90° apex was used as an indenter. The samples were polished before testing. A measuring microscope was used to measure the scratch width. Initially, the material surface was scratched under a load of 0.49 N, and the width of the scratch was measured using a metallographic microscope (Fig. 5, b), and the average value of the mark was determined. In the second stage, a load of 0.98 N was applied to the material surface, and the average value of the resulting mark was determined. Based on the obtained results, it was established that according to GOST 27326-87 standard, the hardness of the material is $H_c = 0.72$ N



a b c

Fig5. Pre-scratch (a) and post-scratch (b, c) views of the specimen

By scratching, the hardness of non-metallic materials is determined not under conditions of elastic or plastic deformation, but under conditions of local wear of materials. When a scratch occurs, the material first undergoes plastic deformation, and then rupture occurs when the stresses reach a value corresponding to the wear resistance.

B. Study of material components

The morphological composition of the wear-resistant heterocomposite polymer material, obtained by EDS spectroscopy, was analyzed using the example of 5 zones of different nature (Fig. 6). Structural analysis of the EDS Spot 1 zone (Fig. 7, a) shows that in this zone, the intensity of light absorption of elements Al Kα1 and Si Kα1 is highest, and they are located adjacent to each other. In this zone, the mass fractions of Al Kα1 and Si Kα1 are 10.6 and 10.4%, respectively. In this case, the mass fractions of each of the elements O Kα1 and C Kα1 are approximately 40%, where oxygen may have entered the material during processing. It can be said with certainty that C Kα1 is a form of graphite, which is added to the material as a dispersed filler.

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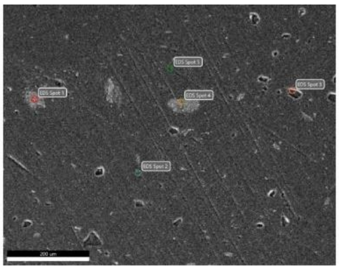

Fig 6. Morphological analysis of the heterocomposite sample, obtained on an EDS spectrometer. x500

Fig. 7, b and c show the structural analysis of the EDS Spot 2 and EDS Spot 3 zones, in both of which the intensity of X-ray absorption of C Kα1 has the highest value, the mass fraction of carbon in these zones is 88.2% and 94.7%, respectively. It can be concluded that both of these zones belong to the graphite, which was added to the composite as a dispersed filler. Since the values of the X-ray reflection intensity of the elements Al Kα1 and Si Kα1 in the EDS Spot 4 zone are close to each other with the X-ray reflection intensity of the EDS Spot 1 zone, we can call them mechanically activated kaolin particle agglomerates in this zone. In this zone, the mass fraction of Al Kα1 and Si Kα1 was 28.5% and 34.4%, respectively. The absence of the element O Kα1 in this zone can be attributed to the fact that its atomic mass is small compared to the mass of the medium from which the material is obtained, which is why it was ejected during processing. The presence of peaks Au Mα and Au Mg on the graph represents the elements of kaolin added as a dispersed filler that were not extracted during the production process.

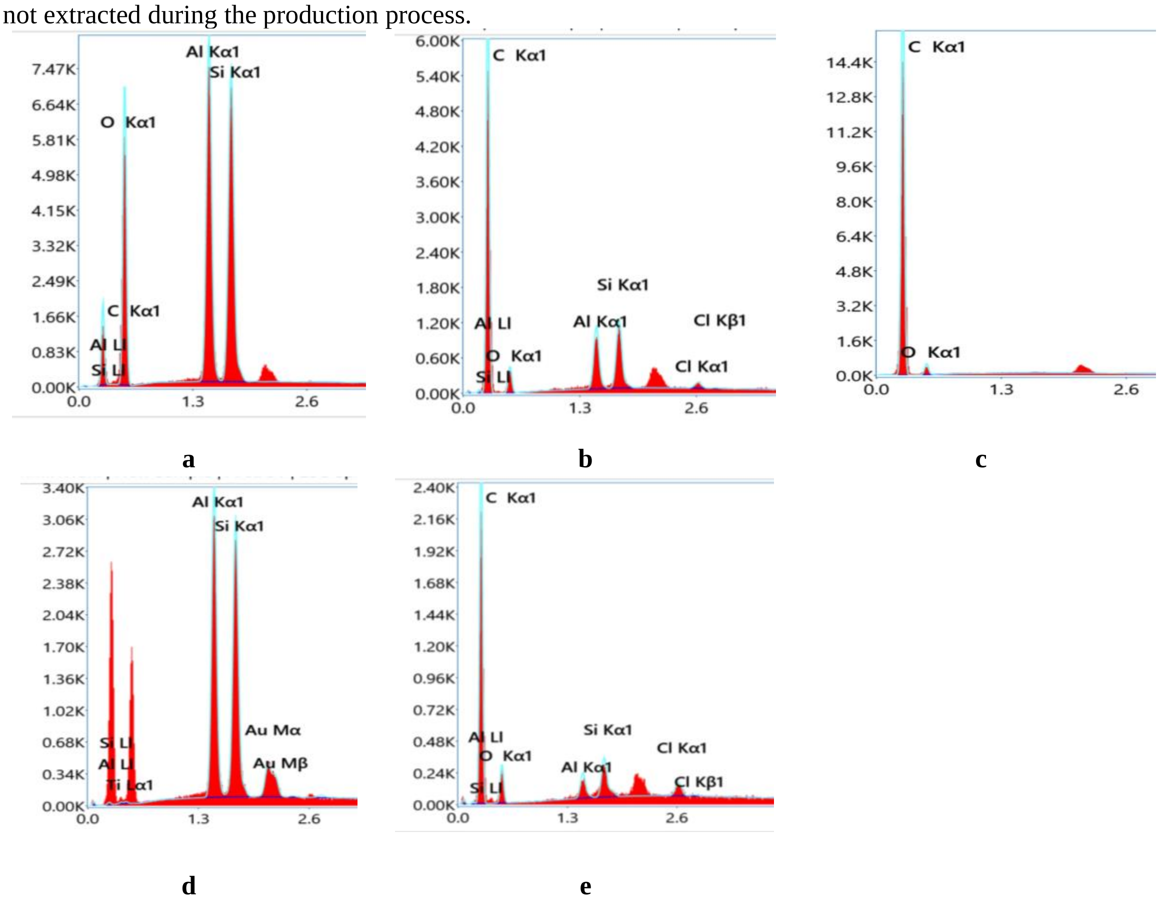

Fig7. Composition analysis of the heterocomposite sample obtained on an EDS spectrometer

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On the graph in Fig. 7, e, the peak C Kα1 corresponds to the characteristic X-ray radiation of carbon, and its value is 85.4%. The highest carbon content in this zone can be attributed to the accumulation of the aggregate of the composite material - dispersed graphite. The presence of peaks Al Kα1 and Cl Kα1/Kβ1 indicates the presence of carbon, aluminum, and chlorine in the sample, but since the mass fraction of these elements is very small, these elements may have entered the graphite during the process of mechanical particle activation.

C. Tribological analysis.

In the cotton industry, in the process of cleaning cotton from small trash impurities, it is possible to increase the service life of the spikes of the loosening drum by coating them with wear-resistant heterocomposite materials. In this process, due to the collision of cotton fibers and the composite coating, rapid wear of the material is observed. The wear of coatings is significantly affected not only by cotton fibers, but also by abrasive particles in the composition of the processed cotton. Therefore, the study of the tribological properties of the spike coatings of the loosening drum plays an important role in ensuring the operational reliability of this part.

To determine the tribological properties of the coating material, coatings were applied to the surface of metal sheets under laboratory conditions. The obtained samples were tested in the "ball-disk" mode in a metal-polymer pair. The test processes were carried out at room temperature (T-23.2°C), constant disk rotation speed (200 rpm), varying radii of friction and duration of time. The change in the value of the coefficient of friction with an increase in the value of the load was analyzed. The obtained results are presented in Table 1.

Table 1.
Dependence of load value and friction time on the coefficient of friction

№	Radius of rotation	t, min/ F, N	1,96	3,92	5,886	7,848	11,77
1	r = 3 mm	10	0,497	0,349	0,477	0,72	0,625
2	r = 5 mm	20	0,328	0,384	0,478	0,72	0,617
3	r = 10 mm	30	0,382	0,457	0,595	0,63	0,559
4	r = 15 mm	40	0,523	0,252	0,324	0,445	0,397
Note: The experimental testing processes were carried out with an increase in the load amount, but without changing the radius of friction.							

In the preliminary test experiment, the rubbing ball was placed at a distance r = 3 mm from the center of the disk, and a force F = 1.96 N was applied to it and rotated for 10 min. Then the pressure force was increased to F= 1.96 N. In this case, the friction coefficient constantly increased for the first 40 minutes and decreased after 40 minutes. At the 50th minute, we can see that the value of the coefficient of friction decreased by 13% compared to the 40th minute. This decrease in the friction coefficient is explained by a decrease in the surface roughness of the composite material in the metal-polymer pair and, as a result, a decrease in the friction resistance force.

The reliability of the obtained results was verified by increasing the friction radius and the experimental test time. In the second experiment, with a rotation radius r = 5 mm, the difference in the values of the average friction coefficients at the 80th minute and the 100th minute was 14%, at r = 10 mm, the difference in the values of the average friction coefficients at the 120th minute and the 150th minute was 11%, at r = 15 mm, the difference in the values of the average friction coefficients at the 160th minute and the 200th minute was 10.7%. Consequently, in the metal-polymer system, the value of the coefficient of friction decreases inversely proportional to the applied load and inversely proportional to the friction time.

IV. CONCLUSION

The conducted research shows that the addition of self-lubricating dispersed fillers, such as graphite, to the composition of heterocomposite polymer materials ensures the wear resistance of the material. However, the addition of these particles by mechanical activation contributes to their absorption into the structure of other fillers, thereby ensuring uniform mechanical properties of the composite material throughout the part volume. Metal oxides in the composition of kaolin, added as a disperse filler, increase the hardness of the composite material and ensure its long service life. A decrease in the coefficient of friction in the metal-polymer pair, directly proportional to the applied load, leads to the conclusion that this composition behaves the same way when in contact with cotton.

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