Проведено аналіз трибологічної ефективності спряжень "полімерних-композитних матеріалів – сталь". Це важливо, оск льки неправильно підібрані матеріли з точки зору трибології дають значні експлуатаційні витрати. Тому вибір марки полімерно-композитних матеріалів для використання у конструкціях вузлів та деталей машин є завданням суттєвого підвищення їх технічного рівня.

Випробування зразків з полімерно-композиційних матеріалів на відносну абразивну стійкість в спряженні зі зразками сталі 45 дало можливість встановити, що найменше значення вагового зношування має матеріал Nylon 66. Найближчими за значеннями відносної абразивної стійкості з досліджуваних матеріалів до Nylon 66 має матеріал ПА-6-210КС, зі значеннями в 1,65 разів меншими. В експлуатації машин при наявності абразивного зношуваннядоцільновикористовуватиспряженняматеріалів "Nylon 66 – сталь 45" та "ПА-6-210КС – сталь 45". Результати триботехнічних досліджень без мащення на машині тертя СМЦ-2 спряжень "полімерно-композитний матеріал – сталь 45" дають можливість встановити, що найменше зношування має зразок з матеріалу УПА-6-30 – 0.00083 г. Найближчим до нього за зносостійкістю є зразок матеріалу PAG/6.6 R196-GF30, що в 6.1 раз більший за ваговим зносом. Зразок з матеріалу сталь 45 в спряжені зі зразком матеріалу УПА-6-30 має найнижче значення вагового зносу 0,00005 г. При цьому найнижче значення коефіцієнту тертя має спряження матеріалів "сталь 45 – УПА-6-30"– 0.163. Процес припрацювання найшвидше досягається з матеріалом УПА-6-30 після 20 хв. зі значенням температури в зоні тертя 348±2 K.

Представлені дослідження необхідні для обґрунтування подальшої експлуатації та підбору полімерно-композиційних матеріалів для спряжень, що працюють у важких умовах. Дані дослідження представляють інтерес для виробників сільськогосподарської і кар'єрної техніки та різних транспортних машин

Ключові слова: полімерно-композитний матеріал, вагове зношування, сталь 45, спряження зразків, коефіцієнт тертя, відносна абразивна стійкість

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ANALYSIS OF TRIBOLOGICAL EFFICIENCY OF MOVABLE JUNCTIONS "POLYMERIC-COMPOSITE MATERIALS – STEEL"

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1. Introduction

Results of operating agricultural machinery by various manufacturers at agricultural enterprises reveal that their rated efficiency is significantly different from actual. A series of essential structural disadvantages have also been identified at forming the moving mating parts of components. The main cause of low reliability of machines and mechanisms is the use, for moving mated parts of tribojunctions, of a material the type of "steel-steel", which demonstrate a low level of tribological efficiency. The proper level of their operation is ensured by technical maintenance, primarily through lubrication, every 40...50 hours of work. Failure to comply with these requirements leads to an abrasive entering the tribojunction of parts causing their rapid deterioration during operation.

Ensuring proper technical condition of moving mated machine parts is predetermined, first of all, by their high tribotechnical characteristics, that is, the proper level of tribological efficiency.

The scientific-technical literature on the use of materials for heavily loaded mating parts notes that for machine engineering the most promising among them under respective operating conditions in agricultural and transport industries are the polymeric-composite materials. Up to now, the physical-mechanical and tribological properties of polymeric-composite materials have not been studied sufficiently enough to substantiate their implementation for movable junctions of machine parts.

To solve the tasks on developing and studying the properties of new materials in this group for mating moving parts of machines, there is a need to prove the experimental feasibility of their application from a tribophysical point of view.

2. Literature review and problem statement

It is possible to use polymeric composites in different sectors due to their satisfactory physical-technical characteristics. Experimental data underlie the physical-mathematical models of a composite material's technological treatment [1]. However, the cited paper did not consider from a tribotechnical point of view the influence of a working environment during treatment on the physical-chemical properties of materials' working surfaces. Currently, the basic additives to polymeric composites are fullerene fillers. Study [2] addressed the influence of adding a fullerene soot in the friction zone with a working oil on certain tribotechnical characteristics of working surfaces of samples from the tribosystem "steel – steel". However, the authors did not consider changes in the characteristics of the tribosystems "steel – polymeric material".

It was established experimentally that polymeric composites demonstrate the effects of scale of fillers, which characterizes the improved mechanical performance of the reinforced polymeric composites, since the sizes of particles or fibers in fillers are usually within a micrometric range [3]. Thus, one should additionally study the tribological characteristics of composites mated with steel samples with different types of fillers. Respective experiments on the polymeric composites reinforced with particles revealed an increase in rigidity when reducing the size of the filler particles at its corresponding volumetric content [4]. Notably, there was no change in the characteristics and properties of the polymeric composites' working surfaces under dry friction modes. It is possible to form high wear resistance and appropriate surface characteristics of metallic working surfaces of samples by adding composite additives to a working oil [5]. In this study, the authors did not investigate the impact of these additives in the presence of abrasive particles. Using wear-resistant and inactive surface layers of materials for tribojunction of parts makes it possible to extend the service life of both separate components and a working environment [6]. However, the authors did not consider the characteristic of relative abrasive resistance of the examined elements of tribojunctions. A series of studies [7] were conducted to explore the possible connection between dimensional effects in clean polymers and polymeric composites. The dimensional effects in composites should be considered based on a tribological point of view, which makes it possible to select materials for mating under specific operating conditions. The theory of elasticity was applied to construct a finite-element approach to solving the tasks on considering the degree of deformation in order to predict the mechanical behavior of composite materials [8]. The authors did not consider the impact of change in the content of fillers in a composite coating and their physical-mechanical characteristics on the change in efficiency of moving mating parts during operation. Experimental results that reflect significant changes in the temperature fields and elasticity modules of composites were reported in [9]; the authors registered a variation in these characteristics towards better results with a decrease in the filler fiber diameter. It would be advisable to additionally consider the effectiveness of ready-made composites with these fillers under the modes of movable contact interaction, which alters the temperature regimes. The results indicating efficiency of using micro-dimensional fillers in polymeric reinforced composites make it possible, from a mechanical point of view [10], to use them under significant normal loads. At the same time, the authors did not specify the change in these characteristics under loads on the moving junctions made from this type of materials. Forming composite coatings makes it possible to increase the durability of mating parts. It was established that the formed composite coatings create an elastic layer, which reduces the degree of deformation in the parts' material [11]. It is advisable to establish regularities of a temperature field influence on the tribological characteristics of moving mating parts with a composite coating. The experimental investigation of the coercive force of the parts' working surfaces confirmed a decrease in the accumulation of destructive stresses in the near-surface layers of the part's material. It was established that some polymers exhibit low thermal properties, which can be improved by adding the nano materials of graphite and graphene additives [12]. The authors did not find the optimal conditions for their use. The impact of abrasive particles on the working surfaces of mated parts creates the conditions for increasing a temperature mode and the conditions for hard-particle grinding [13]. However, the authors did not establish any effect of the wear particle size on the condition of polymeric materials. The use of polymeric composites makes it possible to improve the wear resistance of working surfaces. Based on experimental research, authors of [14] constructed the model for predicting the mechanical behavior and reaction to damage in flat samples of composite materials. At the same time, the authors found no regularities in the influence of normal and tangential stresses on the wear of composite materials and their coatings.

By using nanoparticles, it is possible to obtain better physical properties even at insignificant quantities of types and content of additives [15]. It is therefore important to additionally consider the patterns of tribophysical influence during formation of moving mating parts in machines. The use of polymers has been widely implemented in the controlling elements at seeding equipment, since the materials are low in weight and are corrosion-resistant [16]. Additionally, one needs to consider the impact of abrasive particles in the friction working area of these elements. The increased functionality of composites makes it possible to use different fillers and matrices based on ceramics and siloxane resins to obtain composite materials based on polycrystalline carbon [17]. However, the authors did not establish the tribological characteristics for a given type of the material in different mating materials. Using the methods of scanning and analysis of particle size of fillers during a composite material synthesis makes it possible to create a material with the predefined physical-chemical properties [18]. The authors designed composite materials based on chemical technologies. It would be desirable to group them based on the effect of inorganic, organic, and biological powders, used as a filler with polyacrylamide, on separate properties of composites. Polymeric composites are used for different purposes to replace metallic materials such as steel and cast-iron owing to their elevated strength at low specific weight [19]. In the cited work, it would be advisable to establish relative abrasive resistance of the examined composite in order to clarify the conditions of its use. Based on studies into rheological characteristics, stress fields, as well as deformations of working bodies with polymeric coatings, authors of [20] substantiated new methods to improve the mechanism for treating a technological environment. However, the authors failed to describe the wear mechanism of a given coating in the presence of free abrasive particles. The low values for a friction coefficient were detected when determining the influence of the matrix with a content of 10 % of aramid fibers on the tribological properties of composites [21]. In addition to the specified data, it would be desirable to undertake a research involving the samples of steel under a dry friction mode. The use of wear-resistant polymers is an important niche for conducting tribological studies into a change in the characteristics of composites. The increase in wear resistance was revealed when using acrylonitrile butadiene styrene alumina [22]. It is necessary to establish temperature modes at friction under the modes of dry lubrication. Annealing copper wires with a laser beam makes it possible to detect compositional inclusions in the base matrix [23]. The authors did not study the tribotechnical characteristics of irradiated samples. The introduction of green tribology promotes the development of biocomposites, which makes it possible to use a natural material using a secondary material [24]. It would be advisable to run a comparative analysis of experimental results from industrial composites. By using the methods of internal friction and optical microscopy, authors of [25] revealed compositional inclusions following the effect of a laser beam, which makes it possible to change the physical properties of a basic material. The authors did not establish the basic tribological characteristics of the resulting material. Construction of composites based on ferrites and epoxy resin makes it possible to change a material's properties such as electrical conductivity and wear resistance [26]. In addition, it was necessary to consider the capabilities of a given material under the modes of significant dust and abrasion. Considerable influence on the accumulated wear of elements and parts of foundry machines during the formation of a polymeric composite is exerted by its matrix and the filler [27], which must be taken into consideration in a production process. In addition, the authors did not consider any change in the technical parameters for the process of casting a polymeric composite on the wear of equipment parts. Modeling the conditions and parameters during formation of composites should be considered based on a "white box" procedure. The use and description of a given procedure was formed for a transportation process [28]; with some refinements, it could be adapted to automate the calculation of a technological process for polymer composites formation. In recent years, polymer nanocomposites have been used to manufacture components of various tribosystems [29]. The brief review of the use of polymeric materials for the tribosystems of machines did not reveal any basic recommendations for their use under actual operation modes. The implementation of composites is widespread for the elements, nodes, and components in aircraft engineering, automotive industry, in other sectors, as these materials are characterized by a sufficient ratio of strength to weight, thermal stability, and a good resistance to oxidation and corrosion [30]. At the same time, no regularities in the abrasive resistance and the degree of conjugation have been established for the examined composites.

To improve the quality of experiments associated with the formation of a composite, authors of [31] conducted a micromechanical modelling of the fibrous-reinforced composites to determine the elastic properties of the homogenized material. However, they did not consider such additional starting parameters as the tribotechnical characteristics of a simulated material. It is possible to form an equal-strength filler to a polymeric composite by using tissues based on carbon fibers in an epoxy matrix [32]. A given composition is effective for use in the temperature-loaded little-moving tribojunctions; however, the authors did not consider its capabilities at boundary nodes of lubrication with a significant friction rate. A transmission assembly significantly affects reliability of a vehicle as its parts operate under an alternating load, typically within the range of large loads, which causes rapid failure of individual parts made from composite materials [33]. This can be achieved through the introduction of separate composite parts, but the authors failed to consider the polymeric-composite type of a material to ensure the operational reliability of the assembly. It is possible to form considerable strength of polymeric composites by adding chopped eggshell in a polyester [34]. It was necessary to determine the optimum concentrations of these additives and the maximum values for the tribotechnical characteristics of the examined composite. Basalt possesses good tribological properties as a filler. It provides excellent physical and mechanical properties such as hardness, compressive strength, color, and luster of a polymeric composite [35]. At the same time, the authors did not study the influence of its content on a value for abrasive stability with steel samples. By employing the software HyprChem and a quantum-chemical modeling method, authors of [36] studied the intermolecular interactions between an epoxy-amine mesh and the oxides of various chemical nature Al_2O_3, Fe_2O_3, TiO_2, CaO, which allowed them to establish their significant chemical stability. At the same time, the authors failed to define the value of their tribological efficiency in mating with metals. It is possible to improve safety of road transport by using a composite material that makes it possible to increase the level of crack-resistance of parts and enhance reliability of the examined tribosystems [37]. The authors did not analyze the ability of composites based on ultra-dispersed carbon powders to solve the experimental task. It is possible to experimentally detect and evaluate the thermal properties of polymeric composites with graphene based on differential scanning calorimetric tests [38], which enables the clarification of operating conditions for a given type of the composite. At the same time, the authors did not consider additional heating of the composite in the process of friction. When choosing the required composite, one needs to know the characteristic of its durability depending on the load and the speed of sliding. A research reported in [39] was carried out for the following types of materials: polyphenylene sulfide+ fiberglass (9:1) and polyphenylene sulfide+carbon fiber+graphite (8:1:1). It was found that these materials are suitable for tribosystems with liquid lubrication. It would be advisable to conduct a research into abrasive resistance under the modes of dry friction. To ensure good strength and specific weight characteristics, [40] applied composite sandwich panels, which is relevant for rocket science and aircraft engineering. These materials are light and can withstand significant axial loads. The authors should have identified the impact of these composite structures on tribological mated parts, which could be relevant for mechanical engineering.

There are the following advantages of using polymeric-composite materials in comparison with conventional metallic materials: eliminating the "wedge" effect – due to the special tribological and strength properties of a material, the identified transfer effect, the minimal wear of metallic mated parts in a tribojunction.

The use of polymeric-composite materials is certainly promising in terms of improving the durability of moving joints of machine parts. Therefore, it is advisable to perform a tribological study, for certain groups of parts, on the effectiveness of their use under harsh operation conditions, which can be modeled under laboratory conditions.

3. The aim and objectives of the study

The aim of this study is to experimentally determine the tribological efficiency of mating parts made from steel and polymeric-composite materials.

To achieve the set aim, the following tasks have been solved:

– to conduct a research into mating parts made from materials "steel 45-polymeric-composite material" for relative abrasive resistance;

– to define the tribotechnical characteristics of mated parts made from materials "steel 45-polymeric-composite material" at the friction machine SMC-2;

– to determine the influence of conjugated polymeric-composite materials on the working surfaces of steel materials at friction based on studies into their metal- graphical properties.

4. Materials and methods for a tribological study of the mated samples "polymeric-composite materials – steel"

Our study was based on samples made of steel 45 and the polymeric composite materials (PCM). Six grades of high molecular weight compounds were selected from materials shaped in the form of granules or balls (Fig. 1).

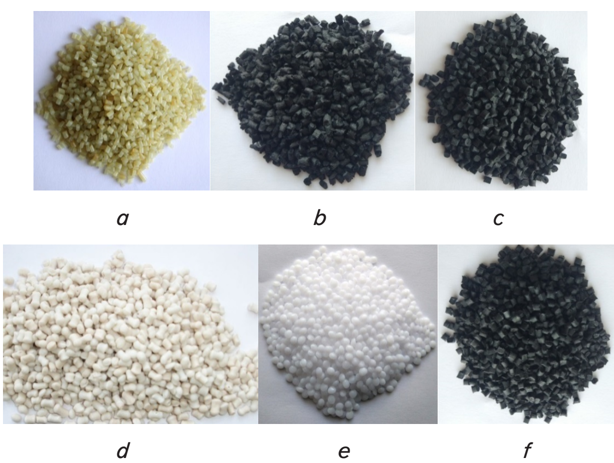


Fig. 1. Physical appearance of PCM granules selected for experimental research: *a* – Nylon 66; *b* – PA-6-210KS; *c* – PA6/6.6 R196-GF30; *d* – Kocetal GF705; *e* – Kocetal K300; *f* – UPA-6-30

We conditionally coded the chosen materials from a polymer group to be examined: Nylon 66 – No. 1, PA-6-210KS – No. 2, PA6/6.6 R196-GF30 – No. 3; from a Kocetal group: Kocetal GF705 – No. 4, Kocetal K300 – No. 5, UPA-6-30 – No. 6.

By analyzing these materials, it is possible to note: Nylon 66 is an unfilled analog of the locally produced "Polyamide-6.6". PA-6-210KS is a glass-filled polymeric composite based on polyamide 6. PA6/6.6 R196-GF30 is a polymeric composite based on polyamides 6 and 6.6 with an addition of black fiberglass, it may contain technical carbon. Kocetal GF705 and Kocetal K300 is the group of cocetals with added fiberglass. UPA-6-30 is a carbon fiber based on polyamide 6 with the addition of cellulose hydrated carbon fibers the brand of "Ural-24 TM".

We fabricated samples from polymeric-composite materials by casting under pressure at the foundry machine PL-32 (Fig. 2), which implements the required technological operations for the manufacture of finished products. Before loading into the machine, the materials were in the shape of cylindrical granules with a length of 2...4 mm and a diameter of 2 mm.

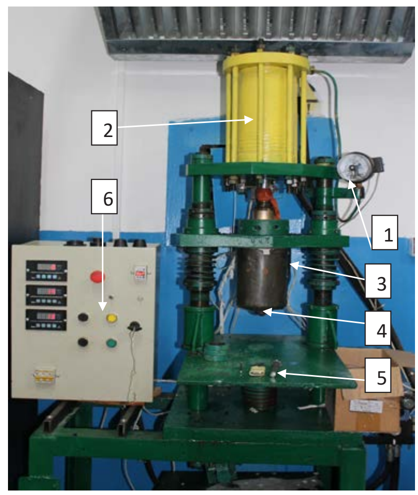


Fig. 2. Foundry machine PL-32: 1 – manometer; 2 – hydraulic cylinder; 3 – heating chamber; 4 – nozzle; 5 – platform; 6 – remote control

The technology of manufacturing experimental samples and parts implied the following. The starting material was poured into heating chamber 4, with a temperature of the melted material (selection was performed experimentally). Temperature in the heating chamber was controlled by a thermocouple. The casting pressure control was enabled by manometer 1, installed inside hydraulic cylinder 2. Control was executed from control unit 6. The assigned temperature was maintained within ± 5 °C. We cast the melted material into a mold placed on platform 5 through nozzle 4 with a hole diameter of 4 mm.

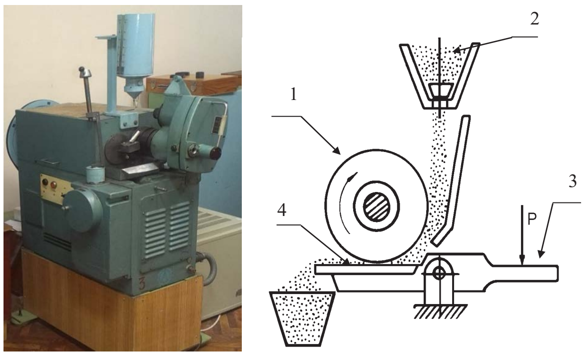
The fabricated samples involved in the research for abrasive resistance were of linear dimensions 53×29×7 mm, which corresponds to GOST 23.208-79 (Fig. 3).

We studied the samples for abrasive resistance at the specially prepared laboratory equipment (Fig. 4), installed at the friction machine SMC-2.

The method to study materials for abrasive resistance implied that under the same conditions we induced the forced wear of the examined and reference samples. The wear was accomplished by using an abrasive non-rigidly fixed material (electrocorund No. 16-N, GOST 3643-71), which was fed to the friction zone and pressed against the sample with a rotating rubber roller (Fig. 4, *b*).

a *b* *c* *d* *e* *f*

Fig. 3. Physical appearance of samples for determining abrasive resistance: *a* — No. 1; *b* — No. 2; *c* — No. 3; *d* — No. 4; *e* — No. 5; *f* — No. 6



a *b*

Fig. 4. Friction machine SMC-2 with the equipment to implement abrasive wear process: *a* — overall view; *b* — equipment scheme: 1 — rubber roller; 2 — abrasive material; 3 — load forming mechanism; 4 — sample of the examined material

Prior to testing, the abrasive was dried to a relative humidity not more than 0.16 %. The roller was adjusted by a friction method, by rubbing the surface with a type 2 grinding paper (GOST 6456-75) with grit No. 8P (GOST 3647-71), fixed in the sample-holder at a flat steel plate. Following the adjustment, the roller was washed in gasoline. Test conditions were as follows: load N (44 H); roller rotation rate, ω (1.0 rps). Characteristics of a rubber roller: diameter d (0.05 m); width a (15±0.1); hardness by GOST 263-75 on the Shore scale A (78...85); relative resulting elongation, % (15...20).

The weight magnitude of samples' wear was determined by weighing at the analytical scale VLR-200 (HGF1); the minimum permissible value is 0.05 mg.

Relative wear-resistance of the examined material was calculated from formula:

$$K_u = \frac{U_e \cdot \rho_d \cdot n_d}{U_d \cdot \rho_e \cdot n_e}, \tag{1}$$

where U_e, U_d is the wear of the reference and examined samples, kg; ρ_e, ρ_d is the density of the reference and examined materials, kg/m^3; n_e, n_d is the number of roller rotations when testing the reference and examined samples.

The density of samples ρ was determined by a hydrostatic weighing method according to GOST 15139-69.

To compare the relative abrasion resistance of the examined PCM samples simultaneously, the reference material Nylon 66 was selected, whose absolute wear magnitude was taken equal to unity.

The tribotechnical characteristics of materials for the parts of moving joints with PCM at lubrication-free fraction were determined at the friction machine SMC-2 (Fig. 5, *a*) according to the procedure given in paper [2]. Readings from the potentiometer KSP-2 (Fig. 5, *b*) for measuring the magnitude of torque and determining the coefficient of friction were recorded on a special diagram paper, GOST 7826-75. The test was carried out according to the scheme "disc-pad". Samples from PCM had a homogeneous structure of cylindrical shape, 15 mm in height and a diameter of 10 mm, radius of the mated steel sample was r=0.025 m.

a *b*

Fig. 5. Overall view of the machine to test the samples for friction and wear and its control panel with the potentiometer KSP-2: *a* — general view of the friction machine SMC-2; *b* — control panel SMC-2 with the potentiometer KSP-2

Before the start of each test, the samples were rubbed. That was necessary to ensure that the friction surfaces of the samples were parallel in shape and the contact area was at least 85 %.

Slip friction coefficient was determined from formula:

$$f = \frac{M_{kr}}{N \cdot \Delta}, \tag{2}$$

where M_{kr} is the torque arising on a disk, N·m; N is the load on a sample, N; Δ is the step of paper, m. For all experiments, the latter parameter was Δ=0.0025 m.

Temperature in the friction zone was measured using the chromel-allumel electronic thermocouple "Termometer 301 Type K" (China). The hole for measuring temperature was executed to a depth equal to half of the sample diameter, and at a distance of 1 mm from the friction surface.

The contact area of the tribojunction "disc-pad" was 2 cm^2. The study mode was as follows: specific pressure on a sample p=0.5 MPa, linear velocity of slip v=0.785 m/s. The process of adjusting occurred under the following modes: maximum specific pressure p=0.25 MPa, slip speed v=0.785 m/s. We believed that the process of adjusting was finished when reaching the area of contact between the pads and the mated sample of 85 % of the projection area.

To reproduce the harsh conditions of operation of materials used in the moving joints of the samples, we studied the tribotechnical characteristics at the friction machine SMC-2 under in the following mode: linear slip speed v=0.785 m/s; specific pressure on a sample p=1.0 MPa.

Metallographic study of the working surfaces in movable junctions of samples was carried out using the microscope MBI-6 (Fig. 6).

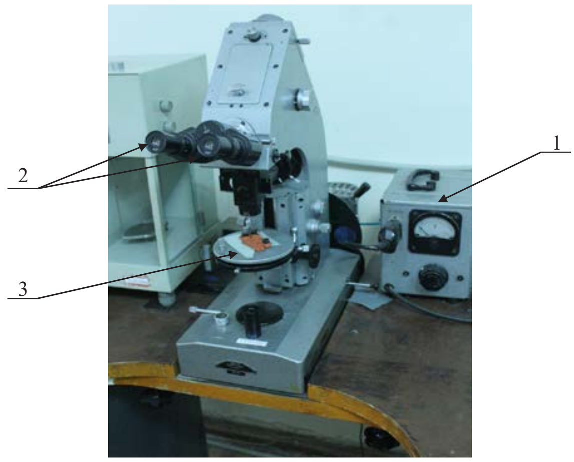


Fig. 6. Optical microscope MBI-6: 1 — power supply, 2 — ocular node, 3 — table for the examined samples

Images of the examined local areas of the friction zone were sent, by using a specialized ocular digital camera, to a PC for analyzing and registering the results in the form of a digital photograph. Metallographic study was carried out with a maximum magnification of up to ×400 times. Surface roughness of the mated samples before testing was not larger $R_a \leq 0.63$ µm. The devised procedure makes it possible, based on experimental results, to evaluate the tribological efficiency of mating parts made from materials steel 45 and the examined PCMs.

5. Results from studying the tribological efficiency of movable mating parts "polymeric-composite materials – steel"

Following our study into relative abrasion resistance of PCM, the samples had an overall appearance shown in Fig. 7; experimental values are given in Table 1.

a *b* *c* *d* *e* *f*

Fig. 7. Overall view of samples made from polymeric-composite materials following the study for abrasive wear: *a* — No. 1; *b* — No. 2; *c* — No. 3; *d* — No. 4; *e* — No. 5; *f* — No. 6

The values for samples made from PCM for the criterion of relative abrasive resistance are shown in Fig. 8.

One can see that the polymers and composites based on polyamides (No. 1–3, 6) have a higher wear-resistance than the polymers from the Kocetal group (samples No. 4, 5).

Table 1

Results of experimental study of PCM samples for abrasive resistance (test duration: 10 min.)

PCM code	Average weight wear, g	Density, kg/m^3
No. 1	0.1624	1,125
No. 2	0.2400	1,340
No. 3	0.2870	1,350
No. 4	0.7488	1,603
No. 5	0.4200	1,365
No. 6	0.3005	1,206

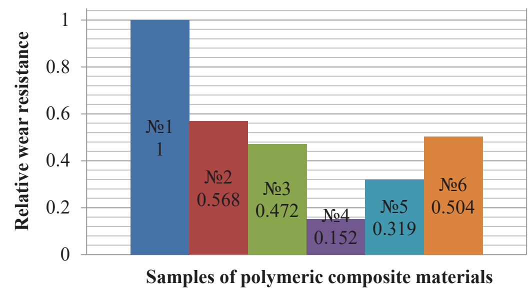


Fig. 8. Results of ranking the experiments to study samples made from PCM for the criterion of relative abrasive stability

Results from a tribotechnical study of wear under conditions of friction without lubrication of tribojunctions with PCM are shown in Fig. 9.

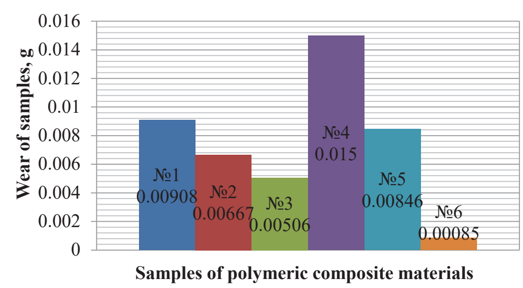


Fig. 9. Magnitude of the weight wear of polymeric samples at friction without lubrication on steel 45 (conditions of experiments: p=0.5 MPa, v=0.785 m/s)

One of the main criteria when studying the operation of the mated parts "polymeric composite-steel" is the magnitude of wear for the steel sample mated with a PCM (Fig. 10).

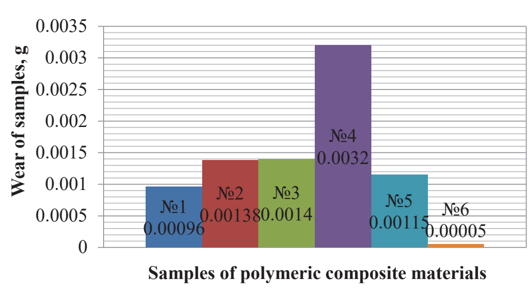


Fig. 10. Magnitude of weight wear for a steel sample at friction without lubrication mated with polymeric samples (conditions of experiments: p=0.5 MPa, v=0.785 m/s)

Determining a coefficient of friction f_{fr} for the mated samples showed that its value is in the range of 0.163...0.491 (Fig. 11).

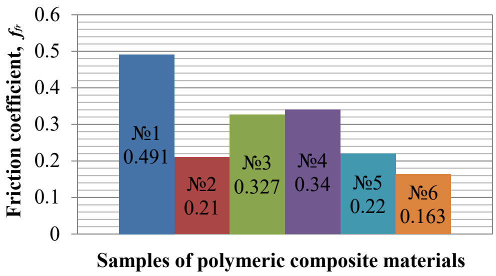


Fig. 11. Maximum value for a friction coefficient at friction interaction between a steel sample and the mated polymeric samples

Variation in a friction coefficient f in the course of the experiment is shown in Fig. 12.

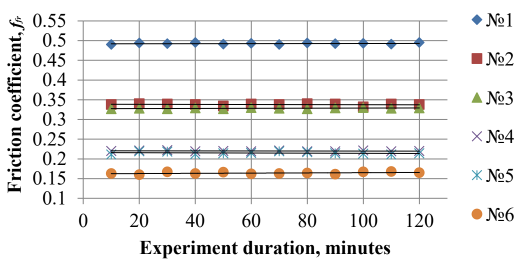


Fig. 12. Dependence of friction coefficient at friction interaction between the mated steel sample and polymeric-composite samples on the experiment duration

Results from studying the temperature in a friction zone, shown in Fig. 13, indicate the correlation between this parameter and the values of friction coefficient f_{fr} (Fig. 12).

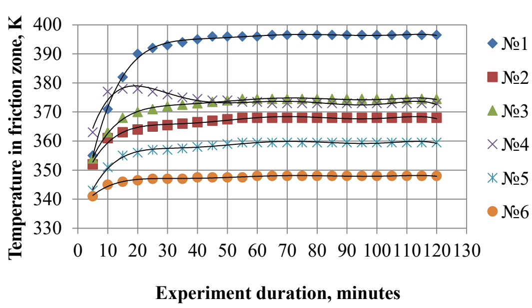


Fig. 13. Dependence of temperature in a friction zone at frictional interaction between the mated samples made from "steel 45 – PCM" on experiment duration

Stabilization of temperature T in the friction zone for all samples demonstrates the proper adjustment of the tribojunction "steel 45 – PCM".

Results from a metallographic study of the surface of friction of the mated samples made from steel 45 with the corresponding examined samples made from PCM are shown in Fig. 14.

By analyzing the experimental results obtained, it is possible to select the materials for mating machine parts under harsh operating conditions using such materials as steel 45 and PCM.

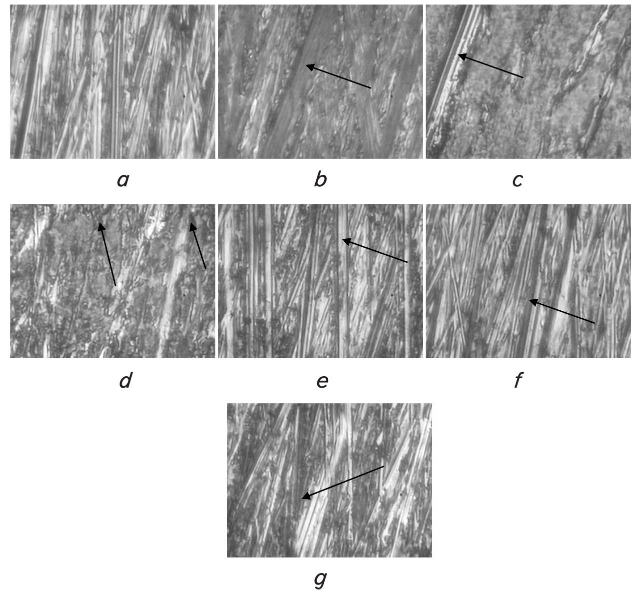


Fig. 14. Characteristic appearance of the working surface of samples made from steel 45: *a* – prior to interaction with samples made from PCM; *b* – following the interaction with PCM No. 1; *c* – No. 2; *d* – No. 3; *e* – No. 4; *f* – No. 5; *g* – No. 6 (×400)

6. Discussion of results from studying the tribotechnical efficiency of mating materials "steel 45 – examined PCMs"

The research results (Table 2) revealed that sample No. 1 (Nylon 66) demonstrates the highest relative abrasion resistance and it is significantly different from other materials. Visual ranking of the samples based on the criterion of relative abrasive stability (Fig. 9) has shown the lowest abrasive wear resistance for material 4 (Kocetal GF705), which is 4.3 times lower than reference No. 1 (Nylon 66). Therefore, it is advisable to use, for mating parts at abrasive wear, the mated materials "steel 45 – PCM No. 1 (Nylon 66)".

The results shown in Fig. 10 indicate that under the same conditions of testing the minimum wear was demonstrated by samples No. 6 (UPA-6-30) (0.83 mg), and the maximum – by sample No. 4 (Kocetal GF705), which is 18.1 times greater than that of material No. 6 (UPA-6-30). In this case, Fig. 9 shows that materials No. 1 (Nylon 66) – No. 5 (Kocetal K300) have the magnitude of wear that is an order of magnitude greater than No. 6 (UPA-6-30). In terms of tribotechnical characteristics without lubrication, the closest one to sample No. 6 (UPA-6-30) is sample No. 3 (PA6/6.6 R196-GF30), whose wear is 6.1 times higher, under the same conditions for conducting an experiment.

The wear results for a steel sample (Fig. 10) show that all PCMs, except No. 6, exert significant negative impact on the wear of the steel sample. Compared with sample No. 6, other samples demonstrated the wear that was higher by 19.2 times (No. 1 (Nylon 66)) and 64 times (No. 4 (Kocetal GF705)). This indicates the impossibility to use materials No. 1 (Nylon 66) – No. 5 (Kocetal K300) for movable junctions of parts operating in mating with the structural steels, heat-treated to a hardness of 48 50 HRC.

Based on the data obtained (Fig. 11), one can argue that the materials of samples No. 2 (PA-6-210KS), No. 5 (Kocetal K300), No. 6 (UPA-6-30) relate to the antifriction ones, since their coefficients of friction f_{fr}<0.3. The materials of samples No. 1 (Nylon 66), No. 4 (Kocetal GF705), No. 3 (PA6/6.6 R196-GF30) are the friction materials with a moderately high friction coefficient.

Our study of the dependence of friction coefficient f_{fr} on experiment duration (Fig. 13) has shown that the stabilization of f_{fr} for all samples occurs in 3…22 min. from the test onset. For samples No. 2 (PA-6-210KS) – No. 6 (UPA-6-30), f_{fr} did not grow for 120 minutes, or deviation of its values were within the limits of measurement error. Only when testing a sample made from PCM No. 1 (Nylon 66) did this indicator slightly grow in a steady fashion. The rate of its growth was 0.01 $(h)^{-1}$.

One of the positive factors for all materials made from PCM, except for No. 1 (Nylon 66), is the stabilization of the friction coefficient of the samples' tribojunctions under a constant mode, which makes it possible to predict their operational reliability in the tribojunctions of parts without lubrication.

One can see that, in general, the regularity of temperature distribution among the samples is almost correlated with f_{fr} (Fig. 12).

From experimental testing, the threshold temperature value for the movable tribojunctions of agricultural machines is 333 K [16]. According to the dependences shown in Fig. 13, two materials satisfy this requirement: No. 5 (Kocetal K300) and No. 6 (UPA-6-30). In other cases, the samples' temperature in a friction zone in tribojunctions is much higher than the recommended. It was established that a minimum temperature in the friction zone was demonstrated by sample No. 6 (UPA-6-30), while sample No. 1 (Nylon 66) demonstrated a maximum, which is 2.72 times higher.

For tribojunctions of materials "No. 1 (Nylon 66) – steel 45" (Fig. 14, *b*), we revealed the characteristic separate minor damage to the steel material's surface (Fig. 14, *b*, indicated by arrows). This is the primary factor for a certain increase in the wear of the sample's surface. The transfer of the polymer to the surface of the mated sample is weakly manifested and plays no significant role in the operation of the tribojunction.

Slightly larger number of grooves was found at the steel sample's working surface at friction with sample No. 2 (PA-6-210KS) (Fig. 14, *c*). This may be due to the presence of glass fibers, which predetermine scratches and contribute to their propagation. In this case, also characteristic is the more pronounced transfer of the polymeric material onto the surface of the steel mated sample. It was discovered that small scratches were filled with a polymer to form a smoother surface of friction. This ensures a low coefficient of friction (Fig. 12).

Material No. 3 (PA6/6.6 R196-GF30) is characterized by local destructions (indicated by arrows), which, judging by Fig. 14*d*, 9, lead to such a character of wear for a steel part that is similar to when using a sample made from PCM, No. 2 (PA-6-210KS).

Friction interaction between material No. 4 (Kocetal GF705) and steel 45 is characterized by large-scale damage (scratches, punching, cutting) to the surface of a steel mated sample (Fig. 14, *e*). This leads to the largest wear of steel material in comparison with other samples. There are no traces of the polymer material transfer to the steel sample's surface, indicating that there are no favorable conditions in the friction zone for the formation of the transfer's polymer film.

For material No. 5 (Kocetal K300), damage (Fig. 14, *f*) to the mated steel material is characteristic of previous cases, except for sample No. 2 (PA-6-210KS). In this case, one observes the dependence of damage on the amount of fiberglass in PCM.

We have revealed a slightly different appearance of the friction surface of a steel working surface of the sample after frictional interaction with the sample made from material No. 6 (UPA-6-30) (Fig. 14, *f*). One observes a decrease in the depth of damage as well as the advanced filling of grooves' bottoms with a polymeric composite (indicated by black arrows). This indicates a clear presence of the composite transfer effect, which ensures minimal wear of the sample's steel surface and the low values for a friction coefficient and temperature in the friction zone.

Among the examined PCM, No. 6 (UPA-6-30) has the best complex of tribotechnical characteristics, necessary to ensure the durability of operation of the tribojunctions of steel parts with the parts made from this PCM. Therefore, this material should be recommended for making parts of tribojunctions, which are operated under harsh conditions.

The main range of industrial PCM have currently basic limits for the temperature regimes of their operation, which is why the maximum value for this parameter is 368…412 K [38]. The examined samples of PCM did not go beyond these limitations during tribological tests in terms of temperature in the friction zone. This once again confirms their compliance to the modeled modes of operation. A promising direction for the current study is to experimentally establish the operating modes of movable mating parts, with the possibility of economic feasibility of producing parts from PCM and implementing them in the engineering technology and technical maintenance of machines.

7. Conclusions

1. Results from our study of samples of polymeric-composite materials for relative abrasive resistance when mated with steel 45 have made it possible to establish that the smallest value of weight wear was demonstrated by material No. 1 (Nylon 66), which was chosen as a reference. The closest values to the reference for the respective abrasive resistance among the examined polymeric-composite materials were demonstrated by material No. 2 (PA-6-210KS), 1.65 times smaller. For normal operation of mated materials under conditions of abrasive wear, it is advisable to use "PCM No. 1 (Nylon 66) – steel 45" and "PCM No. 2 (PA-6-210KS) – steel 45".

2. The results from a tribotechnical study of mating materials "steel 45 – PCM" without lubrication at the friction machine SMC-2 helped establish that the lowest weight wear was demonstrated by the sample made from PCM No. 6 (UPA-6-30), 0.00083 g. The closest PCM to No. 6 was demonstrated by sample No. 3 (PAG/6.6 R196-GF30), 6.1 times higher weight wear (0.00506 g). The sample made from the material steel 45 mated with PCM No. 6 (UPA-6-30) has the lowest value for weight wear (0.00005 g), the nearest PCM is No. 1 (Nylon 66), which is 19.2 times larger. It was established that the lowest values for the friction coefficient of the mated parts "steel 45 PCM" were demonstrated by the samples made from PCM No. 6 (UPA-6-30) – 0.163 and No. 2 (PA-6-210 KS) – 0.21. Adjustment is the fastest for PCM No. 6 (UPA-6-30), which

can be observed by a change in temperature in the friction zone; after 20 min. of the experiment the temperature stabilizes at a value of 348±2 K.

3. Based on the metallographic study of the sample's steel surface mated with PCM, the best characteristics were demonstrated by PCM No. 6 (UPA-6-30). The junction with a given material shows a decrease in the depth of damage and the intensity of filling the grooves with a polymeric composite, which predetermines a decrease in the wear of samples made from steel 45.

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