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EXAMINING A MECHANISM OF GENERATING THE FRAGMENTS OF PROTECTIVE FILM IN THE TRYBOLOGICAL SYSTEM "EPOXYCOMPOSITE – STEEL"

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Розроблено епоксикомпозитні матеріали триботехнічного призначення, які здатні реалізувати ефект вибіркового перенесення під час трибовзаємодії. Досліджено вплив різнофункціональних наповнювачів на зносостійкість епоксикомпозитів, що експлуатуються в жорстких умовах навантажувально-швидкісних режимів трибовзаємодії. Визначено хімічний склад і проаналізовано структуру трибоповерхонь епоксикомпозитних матеріалів та контртіла. Встановлено послідовність етапів формування фрагментів захисної мідної плівки на дотичних поверхнях триботіл

Ключові слова: епоксикомпозитний матеріал, порошок оксиду міді, хімічний аналіз, вибіркове перенесення, трибоповерхня, контртіло

Разработаны эпоксикомпозитные материалы триботехнического назначения, которые способны реализовать эффект выборочного переноса при трибовзаимодействии. Исследовано влияние разнофункциональных наполнителей на износостойкость эпоксикомпозитов при жестких условиях нагрузочно-скоростных режимов трибовзаимодействия. Определен химический состав и проанализирована структура трибоповерхностей эпоксикомпозитных материалов и контртела. Установлена последовательность этапов формирования фрагментов защитной медной пленки на соприкасающихся поверхностях трибোтел

Ключевые слова: эпоксикомпозитный материал, порошок оксида меди, химический анализ, выборочный перенос, трибоповерхность, контртело

1. Introduction

Use of polymercomposite materials in friction nodes of modern machines and mechanisms enhances their operational and technical and economic characteristics. It increases the manufacturability and makes it possible to refuse the alloys of nonferrous metals short in supply and to reduce the weight and cost of machinery [1].

In the triboengineering, polymers are not used in their pure form, but mostly as matrices of composite materials, which are reinforced by the finely dispersed and fibrous fillers. This makes it possible to expand significantly the area of application of polymeric materials, which are used for making tooth gear wheels, pulleys, elements of slipping bearings, cam mechanisms, guiding elements, compactors, seals of hinges, etc. For the lightly loaded friction nodes, the polymer materials are used that have high tribotechnical characteristics and can be operated without lubrication. However, low loading capacity, thermal conductivity and heat resistance of polymers require their modification or reduction in the product thickness [2].

A peculiarity of tribointeraction between the modified polymercomposites is the processes associated with the transformation of polyphase structure of surface layers. Therefore, there is a need for a detailed study of processes of diffusion redistribution of elements, selective mass transfer and phase structural transformations of a tribolayer, the formation of which is determined by the phase composition of polymercomposite and the load-velocity mode of frictional interaction [3].

The relevance of present work is in the study of physical and chemical transformations at the tribosurfaces of epoxycomposite materials, which are in contact with a steel counter body. Examining the given processes will allow the stabilization of friction process, the improvement of resistance of epoxycomposites and the management of tribointeraction process.

2. Literature review and problem statement

A peculiarity of the processes that occur in the zone of a tribocontact between polycomposite materials is a creation of protective films, which are formed at friction and are different from the source material by the structure, chemical and phase composition. Dispersed and fibrous fillers, which function as solid lubricants and can be transferred to the surface of a counter body, contribute to the formation of protective film and decrease in the friction coefficient. In some cases, on the contrary, these films can increase wear intensity when changing operating conditions. For example, films are formed during frictional interaction between stainless steel and polymer composites, which contain carbon fiber. These films show lyophilic properties, which cause formation of the juvenile surface of metal and an increase in the rate of deterioration by tens and hundreds times [4, 5].

Self-lubricating materials were proved to have high and stable tribotechnical characteristics under condition of functional adaptation to operational conditions. Reliability of functioning of tribosystems under extreme conditions is predetermined by the capability, embedded into a composite tribomaterial, to restore operational properties under conditions of deviating from the specified working conditions [6].

For the development of wear resistant composite materials based on thermosetting plastics, it is necessary to understand regularities of formation of films of transferred material at the tribosurfaces, the mechanism of their formation and influence of new structures on the friction characteristics. Therefore, to control the process of selective transfer, it is essential to assess the kinetics of tribointeraction, to obtain morphological characteristic of transfer products, and to examine the impact of modes of operation on their transformation [7, 8].

Selective transfer is a complex self-regulating process, which is accompanied by physical and chemical, electrochemical and mechanical phenomena. As a result, these phenomena contribute to the formation of plastic film of thickness 1...2 μm, with a constant number of dislocations and a large number of vacancies, which provides a sharp decrease in friction coefficient (0.01...0.005) and wear intensity (10^{-10}...10^{-12}) [9]. The processes of selective transfer are implemented in the friction nodes bronze-steel, plastic-steel and steel-steel under condition of availability of copper atoms in the friction area [10]. Therefore, for the formation of protective films on tribosurfaces of polymercomposites, it is necessary to have a source of copper atoms, which may be a part of polymercomposites in the form of dispersed particles of copper compounds.

3. The aim and tasks of research

The aim of present work is to define a mechanism for the generation of a protective copper film at the tribosurfaces of epoxycomposite material and a counter body, which are able to work under difficult friction conditions without lubrication.

To achieve this goal, the following scientific and practical tasks are to be solved:

– to explore the impact of multifunctional fillers on the wear-resistance of epoxycomposite materials;

– to determine the wear intensity of epoxycomposites under different load-velocity modes;

– to conduct a chemical analysis of tribosurface of epoxycomposites and a counter body, which are capable to generate protective films;

– to define morphological characteristics of the fragments of a protective film.

4. Technique for examining the wear intensity and structure of epoxycomposites

As a matrix of the developed epoxycomposite materials, we used the epoxy-dian resin ED-20 (manufactured in Russia) (GOST 10587-84) and the solidifier polyethylenepolyamine (TU 6-05-241-202-78). For the reinforcement of epoxypolymers, we used a complex of the following fillers: fluoroplastic powder, scaly graphite, copper oxide (CuO) powder, discrete carbon fiber.

The study of wear resistance was conducted on the friction machine SMC-2 (produced in the USSR) (GOST 3211-72) according to the "disk – shoe" scheme under conditions of friction without a lubricating medium. The sample was placed at the cylindrical surface of a metal counter body, which rotated at the assigned rate. The counter body was made in the shape of a disk from steel 45 (GOST 1050-74) of diameter 50 mm (R_a=3.2). The samples were made of the reinforced material with a square cross-section the size 10×10 mm and of height 15 mm. To increase the accuracy of the experiment, the examined surface of the samples was buffed to increase the actual contact area. The weight of the samples was determined on the analytical laboratory balance of the AVIV S/3-3 type (manufacturer: Nagema, Germany).

The study of the tribosurface microstructure of the samples of epoxycomposites was held on the optical microscope (Axio Lab A1) (manufacturer: Karl Zeiss), a detailed study of individual surface sections, chemical and morphological analysis was performed on the raster electronic microscope (EVO 50) (manufacturer: Karl Zeiss).

5. Study of wear resistance and microstructure of epoxycomposite materials containing antifriction additives

To investigate the tribotechnical characteristics, the polyfilled epoxycomposites with multifunctional additives were formed (Table 1). As an analogue, we chose epoxycomposite material of optimum composition No. 1 [11], which demonstrated capacity to generate a protective film. To intensify the process of selective transfer, the content of copper oxide powder in the examined epoxycomposite material was increased up to 50 mass fractions (No. 2) and 200 mass fractions (No. 3). The introduction of copper oxide powder in the amount of 50 mass fractions is predetermined by the enhancement of mechanical characteristics of epoxycomposites. The content of copper oxide powder in the amount of 200 mass fractions is maximum since under conditions of additional introduction of other fillers, the system becomes highly viscous and non-manufacturable.

Table 1

Composition of epoxycomposite materials

Content of fillers, mass fraction	No. of composition of epoxycomposite material					
	1	2	3	4	5	6
Scaly graphite	8.2	8.2	8.2	8.2	–	–
Fluoroplastic powder	14.6	14.6	14.6	–	14.6	–
Discrete carbon fiber	1.8	1.8	1.8	1.8	1.8	1.8
Powder CuO	5.4	50	200	200	200	200

Tribotechnical characteristics are especially affected by scaly graphite, which acts as a solid lubricant and decreases friction coefficient of the epoxy matrix (No. 4). Compared with scaly graphite, fluororoplastic powder performs a similar function, which is why the presence of graphite powder in the composite may not be necessary, since it increases the tendency of epoxypolymer system for destruction. Given this consideration, fluororoplastic powder was introduced to the next composition of epoxycomposite material (No. 5) instead of scaly graphite powder. To determine the intensity of influence of graphite and fluoroplastic powders on the wear resistance of epoxycomposites, the epoxycomposite material without these powders, containing only discrete carbon fiber and copper oxide powder (No. 6), was formed.

Crushed carbon fiber is introduced into the system for enhancing the impact viscosity of the system since the discrete fibers prevent cracks from spreading.

It was experimentally determined that under assigned conditions of loading and velocity modes of tribointeraction, the epoxycomposite material of optimal composition No. 1 (Fig. 1) had the lowest wear intensity [11]. An increase in the wear intensity at slip velocity (2.3 m/s) for the composites, containing 200 mass fractions of copper oxide powder, is connected with flaking of solid particles. At the initial stage of friction, these particles perform a reinforcing function rather than lubricating function as scaly graphite or fluoroplastic. However, removal of solid lubricants for compositions No. 4–6 decrease wear intensity by 37 %, since these additives also decrease cohesive strength of the epoxycomposite tribolayer.

Research at the higher slip velocity of V=3.6 m/s showed that wear intensity increases by several times, especially for the epoxycomposites, which do not contain scaly graphite. Under this mode of frictional loading, graphite acts as solid lubricant and is more resistant to elevated temperatures that occur under conditions of high slip velocity. High wear intensity may be explained by a high content of copper oxide powder in the epoxycomposite, accompanied by intense destruction of the surface layer during triobointeration [12].

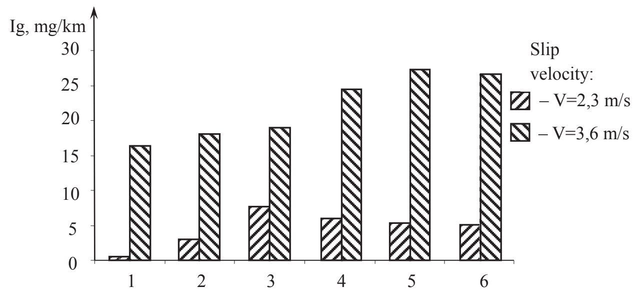


Fig. 1. Intensity of weight wear of epoxycomposites (composition Table 1) at specific loading of 1.5 MPa

Further study of wear resistance of epoxycomposites [12] was carried out at slip velocity of V=3,6 m/s at different specific loading (Fig. 2). With increasing specific loading up to 2 MPa for the epoxycomposites of composition No.1, wear intensity increased by 2.5 times and for composition No. 3 – by 1.5 times. This may be explained by the fact that under more arduous friction mode, the temperature rises, which helps to restore pure copper, the content of which is higher in the epoxycomposite of composition No. 3. A similar situation is evident for the friction mode at specific loading of 3 MPa, when mainly copper oxide powder exist in the composition of epoxycomposite. This powder becomes a source of hosting the copper atoms, which form a protective film.

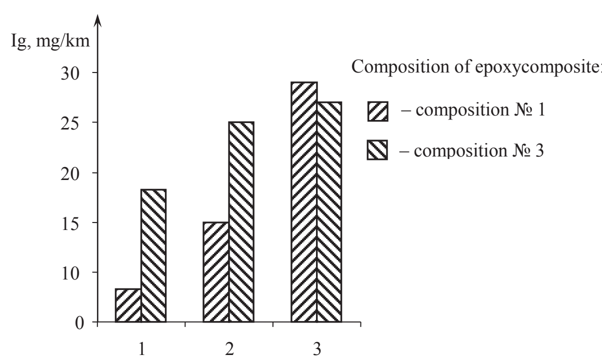
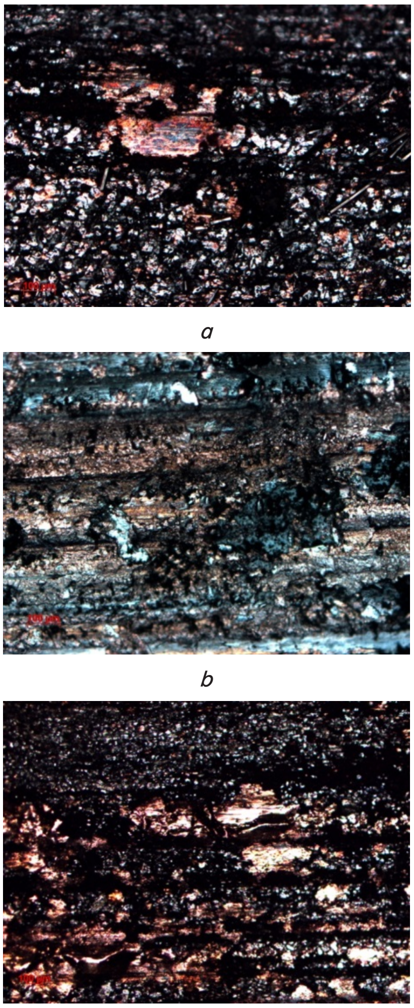


Fig. 2. Dependence of the weight wear intensity of epoxycomposites (composition Table 1) on specific loading: 1 – 1 MPa, 2 – 2 MPa, 3 – 3 MPa

Formation of the fragments of copper film at a tribosurface occurs in epoxycomposite materials with different content of copper oxide powder (Fig. 3, *a–c*). A tribosurface of epoxycomposites is a porous structure that is saturated with the particles of fillers and contains fragments of copper film. The existence of film fragments indicates a re-distribution of particles and wear products, as well as physical-chemical transformations during friction. The fragments of copper films were established to have an elongated shape in the friction direction, which confirms the dominating influence of counter body on the generation of protective film at the tribosurface of epoxycomposites.



a

b

c

Fig. 3. Tribosurface of epoxycomposite of compositions: *a* — No. 1; *b* — No. 3; *c* — No. 6

The surface of the epoxycomposite of composition No. 1 has the least area of the formed film, which is connected with a low content of copper oxide powder (5.4 mass fractions). The film is formed as a local fragment because the number of copper atoms, which are transferred from the surface of the counter body is negligible due to the low content of copper oxide powder in the composite. For the composite, filled with copper oxide powder in the amount of 200 mass fractions (epoxycomposite of composition No. 3), the area of the formed fragments of a copper film is 21.84 % (Fig. 3, *b*) of the total area of tribosurface. In this case, there are many fragments of the formed protective film, but they are small by the area size and not contrast.

For the epoxycomposite of composition No. 6 (Fig. 3, *c*), filled with copper oxide powder and crushed carbon fiber, the area of copper film is larger (37.78 %). Formed fragments of the protective film are clearly visible, since the conditions for the film generation are more favorable due to the lack of graphite and fluoroplastic at the surface. Not very high indicators of wear resistance of the given epoxycomposite (Fig. 1) may be explained by the alignment period, when formation of a protective film started and, accordingly, the surface layer was intensively destroyed compared with the epoxycomposites of composition No. 1 and No. 3 through the lack of lubricant additives (graphite and fluoroplastic).

6. Chemical analysis of the tribosurface of an epoxycomposite and a counter body

At the tribosurface of the epoxycomposite material of composition No. 6, the protective film with the slip lines, located in direction of counter body rotation, was formed (Fig. 4). Chemical analysis of the tribosurface of the given epoxycomposite (Table 2) showed that carbon exists at points 1 and 2 in large quantities – 44.92 % and 49.47 %. This indicates that the thickness of the formed film is insignificant, resulting in device fixing chemical elements of the sub-surface layer.

Point 3 corresponds to the inclusion of copper oxide particles. Carbon content in the given point is 1.3 times lower compared to the previous points and is 34.12 %. The amount of copper is high (42.27 %), while the amount of oxygen (21.27 %) is low compared to other points.

The content of other chemical elements that are present at the tribosurface of epoxycomposite is insignificant and is within 0.15...2.48 %, which does not exert any essential impact on the formation of film structure in the triboint-eraction.

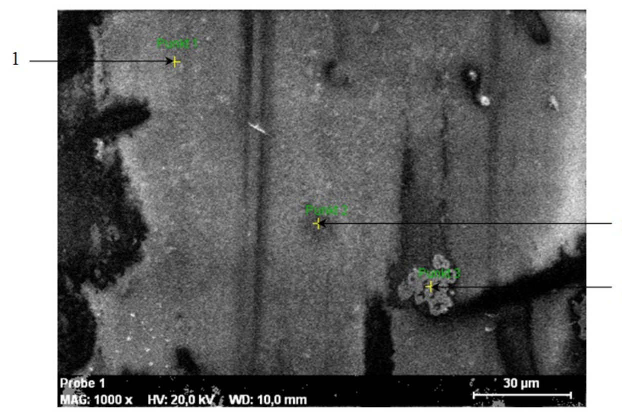


Fig. 4. Chemical analysis of tribosurface of epoxycomposite of composition No. 6

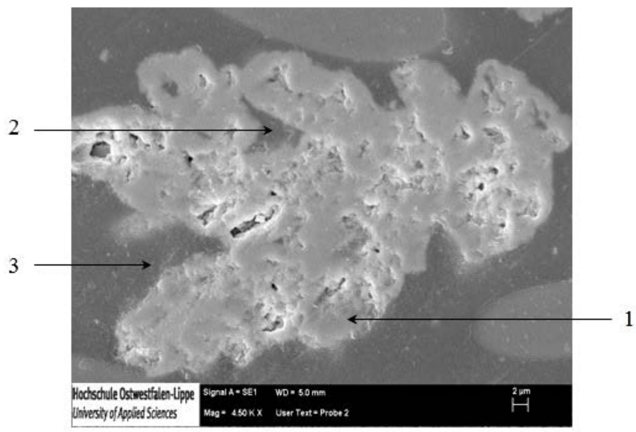
Table 2

Distribution of chemical elements at the tribosurface of epoxycomposite of composition No. 6

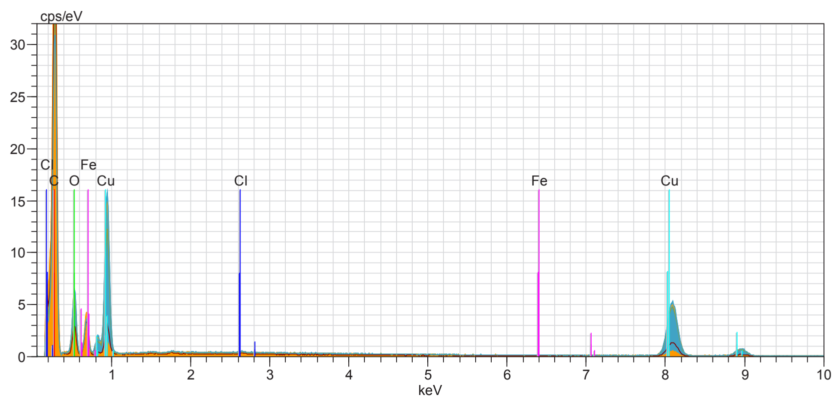
Spectrum, %	C	O	Al	Si	Cl	Fe	Cu
Point 1	44.92	21.03	0.15	0.23	0.23	0.77	32.68
Point 2	49.47	26.60	0.25	0.27	0.22	0.65	22.54
Point 3	34.12	21.27	1.06	0.62	0.27	0.39	42.27

Using the method of chemical analysis, a copper oxide particle, which is located at the tribosurface of epoxycomposite, was identified (Fig. 5). It was found that point 1 corresponds to the highest concentration of copper (42.67 %)

and to the lowest carbon content (35.87 %) (Table 3), which defines a section on the surface of epoxycomposite as the inclusion of copper oxide. Points 2 and 3 with a low copper content (13.25 % and 5.76 %) indicate the section that correspond to the epoxypolymer matrix, since their carbon content is the highest (60.43 % and 67.04 %). The concentration of oxygen in these points is the highest (25.80 %, 26.62 %) compared with point 1 (20.95 %), which indicates the relevance of these points to the epoxypolymer matrix.



a



b

Fig. 5. Chemical spectrum of the section of tribosurface of epoxycomposite, containing copper oxide particle: *a* — microstructure; *b* — chemical spectrum at point 1

Table 3

Distribution of chemical elements on the section of tribosurface of the epoxycomposite that contains a copper oxide particle

Spectrum, %	C	O	Cl	Fe	Cu
Point 1	35.87	20.95	0.16	0.35	42.67
Point 2	60.43	25.80	0.23	0.29	13.25
Point 3	67.04	26.62	0.20	0.39	5.76

Chemical analysis of tribosurface of the counter body, which was in a tribocontact with epoxycomposite of composition No. 6 (Fig. 6), proved the existence of fragments of the protective film, which consists mainly of copper (Table 4). The film is formed as the fragments of elongated shape in the direction of the counter body rotation.

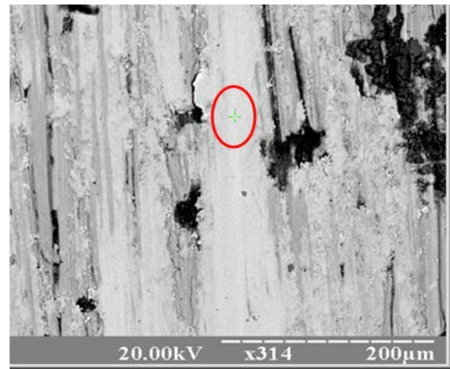


Fig. 6. Chemical spectrum of the section of tribosurface of the counter body

Table 4

Distribution of chemical elements at the tribosurface of counter body

Chemical element	O	Cr	Fe	Cu
Content, %	0.29	0.16	7.73	91.82

It is obvious that the formation of a stable structure as a film of transfer on tribosurfaces is a gradual process. For its formation and stable operation, it is necessary to apply modes of phased frictional loading on condition of introduction of copper oxide powder. The uniqueness of this powder is that it simultaneously performs a reinforcing function for epoxycomposite material and the tribotechnical function for the surface layer. It was proved that this powder is a source of copper atoms for generating a protective film.

6. Discussion of results of examining the selective transfer

The scientific novelty of present work is in the interpretation of a mechanism for the generation of a protective film that is formed in the friction process due to the selective transfer of copper atoms at the tribosurface of the counter body and the reverse transfer of copper particles at the tribosurface of epoxycomposite.

An analysis of triboprocesses and microstructure of tribosurfaces of the system "epoxycomposite – a steel counter body" proves the existence of redox reactions, because the composition of the developed epoxycomposites does not contain pure copper, but only its oxide (CuO). The initialization of these reactions occurs in the area of a tribocontact at the elevated temperature, which happens during a more arduous load-velocity mode of frictional interaction. These reactions take place in the local areas as a result of electrochemical action. Reduction of copper from its oxide (CuO) can take place under condition of interaction with oxide of bivalent copper with hydrogen ($CuO+H_2 \rightarrow Cu+H_2O$), which is contained in the air, and carbon, which exists in the composition of epoxycomposite material ($2CuO+C \rightarrow 2Cu+CO_2$). In this case, the formed carbon dioxide (CO_2) reacts with carbon with the formation of carbon monoxide ($CO_2+C\rightarrow 2CO$), which also interacts with copper oxide, reducing copper ($CuO+CO\rightarrow Cu+CO_2$). The by-product of this reaction is carbon dioxide, which, in turn, again reacts with carbon, which makes the process of copper reduction cyclic and continuous.

According to the Volt row, a steel counter body has negative potential in places of tribocontact, while the composite, which contains copper oxide, has positive potential. The movement of electrons occurs from the negatively charged material of friction pair (steel) to the positively charged (epoxycomposite). At the same time, the movement of atoms of reduced copper, which transfer to the surface of a counter body and interact with it, forming adhesive bonds.

This self-regulating process occurs prior to the moment of generation of continuous film from reduced copper on the tribosurface of a counter body. Further, mechanical transfer of copper particles to the tribosurface of epoxycomposite material occurs, as a result of which it is covered only by fragments of copper film in local places, where there are clusters of copper oxide particles, the surface of which is reduced. Generation of a continuous film on tribosurface epoxycomposites is complicated due to low adhesive strength between a metal film and non-metal epoxypolymer matrix. The process of generation of a protective film on tribosurfaces is more intensive for epoxycomposite that contains 200 mass fractions of CuO compared with epoxycomposite with CuO content (5.4 mass fractions), which promotes attachment of copper particles to the tribosurface of epoxycomposite in the form of local fragments.

Intensive generation of a film on the tribosurface of epoxycomposite, which contains only discrete carbon fiber and CuO powder (200 mass fractions), is caused by favorable conditions. Absence of solid lubricants (fluoroplastic and graphite) on tribosurface promotes an increase in the area of a protective film, because then copper particles join already formed local fragments.

Thus, establishment of the mode of selective transfer would allow us to decrease wear intensity and stabilize friction process in the epoxycomposite materials, which will enhance reliability and durability of tribonodes under conditions of limited lubrication or lack of a lubrication medium.

7. Conclusions

1. We established the growth of intensity of weight wear of epoxymaterials by 16–43 % in the case of increasing the content of copper oxide powder to 200 mass fractions compared with the content of 5.4 mass fractions. It is connected with the fact that under conditions of load-velocity mode of triboInteration, this powder performs only the reinforcing function and flakes intensively.

2. The intensity of weight wear was found to decrease by 10 % in the case of employing the slip velocity of V= =3.6 m/s and specific loading of P=3 MPa. This is explained by the occurrence of favorable conditions for the formation at tribosurfaces of fragments of a protective film, which divides tangent surfaces and acts as a solid lubricant.

3. The existence of fragments of a protective film on the tribocomposite of epoxycomposite (content of copper is 22–32 %) and a counter body (content of copper is 91.82 %) was established. Chemical analysis proved that the tribosurface is covered with the film, which mainly includes copper.

4. The shape and the area occupied by a protective film at tribosurfaces was defined. The size of given area depends on the chemical composition of fillers and their amount. The least area (12.09 %) was occupied by the epoxycomposites with content of oxide powder of 5.4 mass fractions, which is connected with insufficient amount of this filler. The existence of solid lubricants (graphite and fluoroplast), containing epoxycomposite, prevents formation of a film, which is generated at the tribosurface of epoxycomposite in the form of small local inclusions. Introduction to the composition of copper oxide powder in the amount of 200 mass fractions and discrete fiber increases the area of a protective film to 37.78 %, which indicates the optimum composition of epoxycomposite.

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Досліджено технологічний процес пластичної обробки бронзових втулок методом вібраційного деформування. Отримано параметри процесу вібраційного деформування бронзових втулок сільськогосподарської техніки. Досліджені механічні властивості відновлених деталей і їх вплив на експлуатаційні показники робочих поверхонь. Визначено механізм підвищення зносостійкості оброблених вібраційним деформуванням деталей

Ключові слова: вібраційне деформування, пластичність, бронзова втулка, зносостійкість, механічні властивості, відновлення, зміцнення

Исследован технологический процесс пластической обработки бронзовых втулок методом вибрационного деформирования. Получены параметры процесса вибрационного деформирования бронзовых втулок сельскохозяйственной техники. Исследованы механические свойства восстановленных деталей и их влияние на эксплуатационные показатели рабочих поверхностей. Определен механизм повышения износостойкости обработанных вибрационным деформированием деталей

Ключевые слова: вибрационное деформирование, пластичность, бронзовая втулка, износостойкость, механические свойства, восстановление, упрочнение

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RESEARCH OF WEAR RESISTANCE OF BRONZE BUSHINGS DURING PLASTIC VIBRATION DEFORMATION

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1. Introduction

Equipment performance is the ability to perform preset functions in the process of operation. It is estimated by comparing the actual values of parameters with the specifications. The use of new technological processes in the manufacture and reconditioning of parts contributes to the reliability of agricultural machines and units. Insufficient reliability leads to a significant increase in reconditioning and operating costs [1].

A large number of parts made of non-ferrous metals and alloys are used in agricultural machinery. These materials have high antifriction properties and corrosion resistance. They also withstand considerable specific loads and high speeds. Most often these are bronze “bushing” type plain bearings [2].

In practice, vibration treatment is a highly effective method of increasing the wear resistance of machine parts. Thus, the urgency of the work lies in a comprehensive study of vibration treatment of bushings of agricultural machinery. However, this requires determining the optimum values of process parameters.

2. Literature review and problem statement

The use of vibrations has some advantages over conventional treatment methods. This is due to the harmonic vibrations of a workpiece or tool [3]. In [4], the authors note an increase in the metal fatigue resistance under vibro-impact loading. Also, the mechanical properties of a working surface during vibration centrifugal hardening are improved [5]. According to the author [6], application of vibration technologies contributes to resource saving. The authors of [7, 8] also indicate a change in physicomechanical properties of the processed material and the intensifying effect of vibrations. However, there is a lack of data on certain types of parts.