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E-mail: tribosenator@gmail.com

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Хмельницький національний університет, редакція журналу “Проблеми трибології”
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Evaluation of the wear of the duckfoot sweep cultivator blades and the technology of their hardening

T.S. Skoblo, I.M. Rybalko*, O.V. Nanka, O.V. Saychuk

Kharkiv Petro Vasylenko National Technical University of Agriculture, Kharkov, Ukraine
**E-mail: irybalko.ua@gmail.com*

Abstract

In recent years, research and developments related to the creation of new areas using nanotechnology take a special place in scientific achievements. They are developed and widely used in Physics, Chemistry, Biology, Electronics, Medicine, Food Production and to a much lesser extent in Engineering. This is due to the fact that there are different requirements to parts and products used in mechanical engineering, they have a complex shape, are made of different materials, production methods, heat treatment. While operating, their working layer undergoes degradation with a significant change in structure and their hardening using nanocoatings may turn out to be ineffective in both technical and economic aspects. In this case, only a specific approach, which is determined by comprehensive research with identification of the main factors of parts damageability in specific production and operation conditions, can be expedient. In addition, in some cases for hardening, repair and restoration of parts it is expedient to use surfacing methods with the introduction of modifying agents in a liquid bath during crystallization. These modifying agents are nano-and dispersed diamonds, which make it possible to adjust temperature parameters of crystallization, grain size, and stress level. This approach allows using high-alloyed, high-carbon electrodes even for thin-walled steel and cast iron products. In this case, the diamond inclusions additive plays the role of micro-refrigerators, which significantly change the crystallization temperature range. It is important to determine the optimal dose of the introduction of such a modifier and ensure uniform distribution the components in the coating. The presented work is devoted to the new technology development of hardening of cultivator blades metal with nano- and dispersed diamond additives, which are the part of the detonation charge from the disposal of ammunition. Nowadays, in agriculture, a large number of tillage implements are used for tillage, the working bodies of which are sweep blades. They are operated under conditions of abrasive particles impact, and this is accompanied by their intense wear with a corresponding change in the geometric dimensions of the main working surfaces. The worn sweep blades significantly reduce efficiency and quality of the carried-out work. The analysis of the effective choice of surfacing materials for hardening and improving their performance has been carried out and the nature of wear has been evaluated in order to identify areas of maximum damage and to determine the optimal method. It is known that T-590 and T-620 electrodes are used for the restoration surfacing of tillage implements. It was found the hardfacing of thin-walled parts is accompanied by a smaller heat sink and, in some cases, they are flooded with defect formation. To reduce it, a non-magnetic fraction of detonation charge from ammunition disposal in the form of an electrode modification was introduced, which ensured the uniform distribution the components in the coating. The method of the X-ray electron-probe analysis has been used to evaluate features of structure formation and component distribution along the perimeter of the coating. It was found out that this method of hardening reduces heat input and increases the microhardness and wear resistance of the surfaced coating, reduces the transition zone and thermal impact. The recommended method of metal hardening of new cultivator blades is to apply stripes on the point tip and wings of blades. On the basis of the nature of wear, the expediency of applying stripes on the point tip of the cultivator blade from the front side, and on wings from the rear side, is justified. The optimal geometrical dimensions of hardening stripes and their location on the blade are presented, which allows minimizing the local stresses and increasing wear resistance.

Key words: cultivator blades, surfacing, detonation charge, stripes, heat input, modification, structure formation, nano- and dispersed diamonds.

Introduction

The analysis of the literature revealed that about 60% of duckfoot sweep cultivator blades of agricultural machinery lose their working capacity due to the point tip and wings wear. In this case, the point tip wears out by 30 mm, wings - by 15 mm in width. It is observed metal deformation in the working area of wings. Sufficiently a big number of methods for their reinforcing and repair were revealed. All of them are labor-consuming and after their use the resource of working bodies does not exceed ~ 70% comparing to the new ones. Over time, while operating, the metal loses its original properties; its degradation takes place [1]. Worn parts restoration is not considered to be expedient since it is impossible to provide necessary properties simultaneously for all zones of the cultivator blade, taking into account its damage rate. Let us consider some ways to harden new duckfoot sweep cultivator blades.

There is the cultivator working body [2], which includes a duckfoot sweep blade, the working area of which is made in the form of a curved surface, and it passes from the beginning of its point tip to the end on side surfaces. While operating, the cultivator blade profile decreases in the direction of its movement and to preserve consumer properties, refractory metal stripes are formed by surfacing at different angles on its surface. Preliminary assessment of such technology of the cultivator working body blade reinforcing can be effective while operating due to the formation of a cogged profile while operating, which will provide self-sharpening. Such technology of increasing cultivator blades wear resistance is recommended to be used repeatedly during their operation and wear. The disadvantage of this reinforcing method is that stripes are applied only on the blade, which is formed by various methods (surfacing, machining work, plastic deformation, pull-off, etc.), which leads to accumulation of additional stresses in it and they are localized on the blade edge - blade base. Besides that, according to the studies, on the wings of the blades, the maximum wear takes place from their opposite surface, relatively to the blade of the point tip. Therefore, taking into account zones of the biggest wear and the reinforcing scheme adopted by the authors [2], it is impossible to achieve the self-sharpening effect. As for the recommendation regarding additional restorative blade reinforcing when using the equipment, according to this technology, it will also be ineffective. This is due to the fact that while operating the metal of the blade is subjected to wear (thickness decreases by 1 ... 1.5 mm), which during application of stripes by surfacing will contribute to its penetration.

There is also known a method [3] of reinforcing the blade and adjacent to it perpendicularly directed zones of the cultivator blades by stripes surfacing with a wear-resistant material, and in the interstrip zones by creating rows of holes formed while stamping. Such technology is complex and accompanied by incompatible operations in the technological flow chart of production, which uses various approaches for applying holes by stamping and stripes by welding. The use of various technological processes will contribute to the localization of stresses from stripes surfacing by stamping zones, which will lead to the formation of defects and cracks at the holes. The method also does not prevent the deformation of the wings of the blades while operating.

The solution [4] may be more effective in terms of its technological essence and results, increasing service durability of duckfoot sweep cultivator blades. It is aimed at reducing blade wear by applying reinforcing stripes on both of its surfaces, forming a working surface.

The application of reinforcing stripes in this work was carried out according to a different scheme. It was carried out by local processing with a laser beam and this made it possible to apply reinforced stripes of infinitely small sizes on both surfaces of the blade. This treatment does not provide a significant increase in wear resistance because it does not use additional reinforcing by alloying, which can significantly increase the hardness. This method uses carbon steel reinforcing of cultivator blades only due to heat treatment of the shallow depth zones. This is due to the fact that the increase of heat input by this method will lead to crack formation and disruption of the product. This method also will not provide the increase of the blade wear resistance of the cultivator blade wings. In the considered technological solutions of reinforcing methods of duckfoot sweep cultivator blades, specific effective recommendations are also not provided for the parameters of the applied reinforcing stripes, the structure formation and properties achieved in reinforcement zones.

Goal and problem statement

The aim of the study was to develop a method of hardening of thin-walled cultivator blades by applying a programmed coating by hardfacing with a high-carbon alloyed electrode with modification of secondary raw materials for crushing the carbide phase, minimizing the transition zone and the tendency to form defects.

The goal of increasing consumer properties of the cultivator blades can be achieved by changing the reinforcing scheme and stable operation based on a statistical analysis of wear and deformation of such a product, with the subsequent possibility of reinforcing by surfacing with modifying and carbide-containing components of the electrode.

The use of such technology in production requires an innovative approach to obtain reinforcing stripes by electrode surfacing with minimization of stresses, as well as the formation of a metal structure without defects.

Earlier it was carried out some works on modifying by detonation charge from ammunition disposal when restoring parts of sufficient thickness [5, 6], when welding cracks in cast-iron body parts [7, 8]. It was found out that the introduction of secondary raw materials into a liquid bath while surfacing reduces heat input and creates favorable conditions for crystallization of various even non-technological high-carbon alloys. In this work, there was an equally challenging task of ensuring the application of high-quality reinforcing coatings on the thin cultivator blade, taking into account the nature of their wear and damage.

Material and Methods

A significant disadvantage of modern duckfoot sweep cultivators blades with plane deformers is poor-quality soil loosening. The intensification of such an effect due to the cutting edges wear of the cultivator blades has a negative effect on the energetics of the treatment process. In addition, bioactive soil structures break down into dusty, easily subjected to erosion [9].

In this regard, it is of interest to conduct research on cultivator blades wear for new technological process development, which, on the one hand, increases their durability and, on the other hand, improves tillage quality.

Currently, there are no real physical and mathematical models of abrasive wear and formation of the geometry of cultivator blades cutting elements. Determination of the basic regularities of abrasive wear of cutting elements, formation of their optimal geometry, selection of materials for manufacturing and reinforcing, their influence on the technological process of production and operation is an important task in resource improving of tillage machine bodies [10, 11].

It was found out 10] that the process of interaction of machine working bodies with the soil while they are moving is characterized by the abrasive impact on a wedge with a plane or curvilinear working surface. Blade impact on the soil depends on the nature of material deformation, wedge parameters, physico-mechanical properties and condition of the metal, as well as the soil, the speed of machine movement.

Degree of blade abrasive wear in thickness can be represented as a function of the following factors:

$$I_h = f(p, L, H_\mu, S), \quad (1)$$

where p is a normal specific dynamic pressure of the soil; L is a friction path; H_μ is a blade material hardness; t is an indicator of abrasive wear capacity; S is a friction area.

a b c

Fig. 1. Duckfoot sweep cultivator blade of MARATHON SERIES production of OSMUNDSON company: a – new; b, c – worn out

a b c

d e f

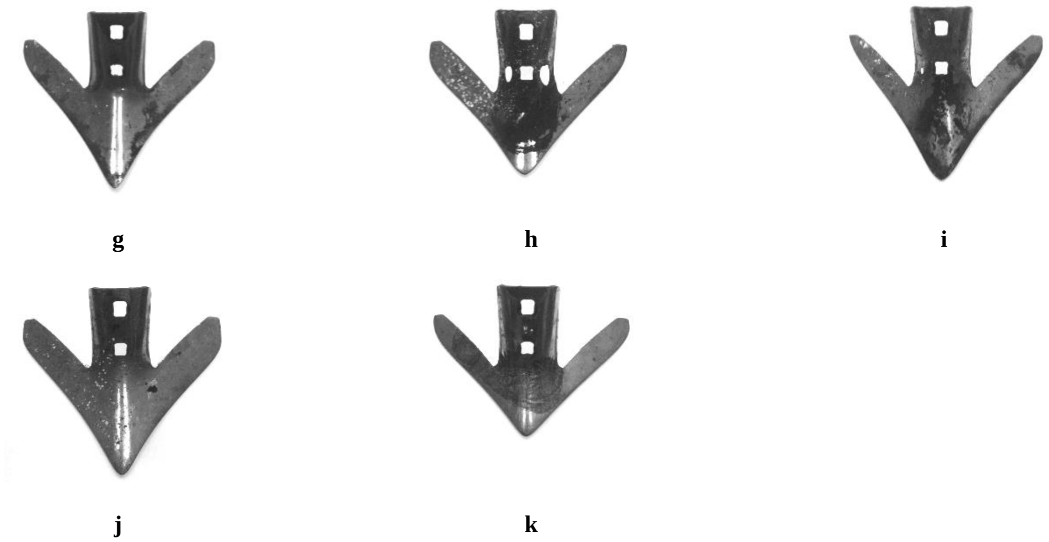


Fig. 2. Duckfoot sweep cultivator blade 9.3 "TigerMate II of CNH company:
a - new;
b - k - worn out

For the analysis of the profile change of duckfoot sweep cultivator blades in operation, products made by MARATHON SERIES of OSMUNDSON firm (Fig. 1) and 9.3 "TigerMate II of CNH firm (Fig. 2) were selected. Both new and used (worn out) under the same conditions (soils) of operation [12, 13] were comparatively studied.

The thickness and main dimensions of wings, grip were checked. Visually, it is seen that their geometrical dimensions differ significantly after operation. A ruler and Miol digital caliper were used to determine the thickness. Main characteristics: measurement accuracy - 0.01mm, measurement range 0-150mm. Blades were measured according to the developed scheme presented in Fig. 3.

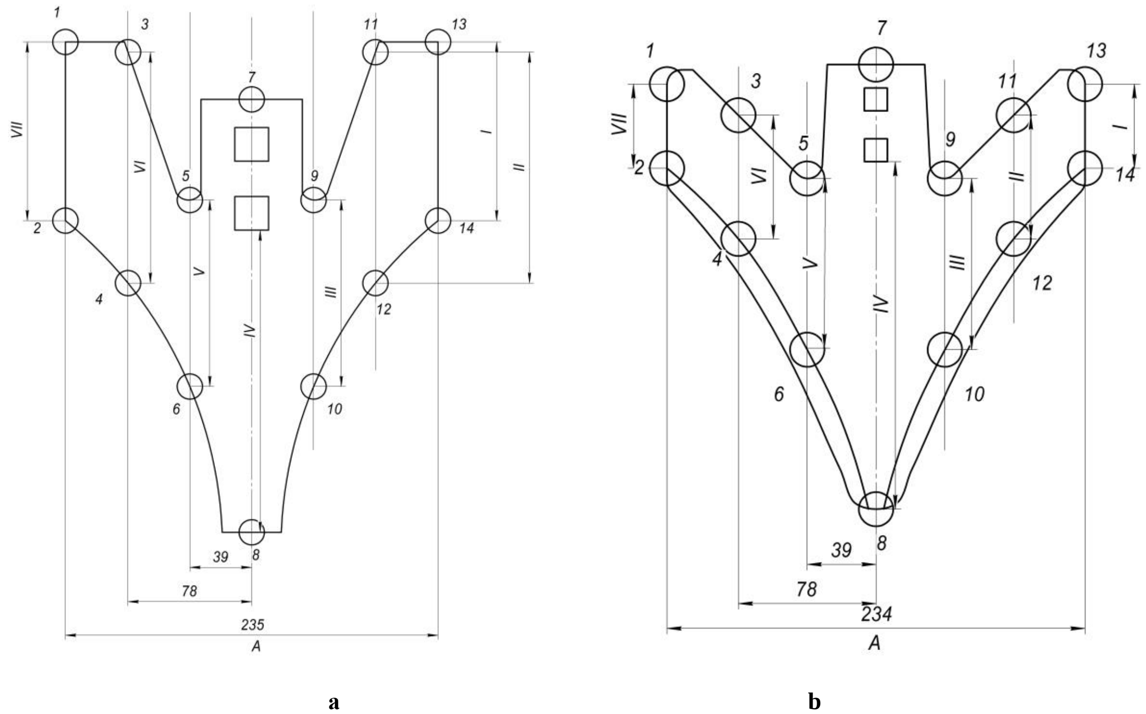


Fig. 3. Measurement of thickness and linear dimensions on new (a)
and worn out (b) cultivator blades of MARATHON SERIES and TM II 9.3"

The circles indicate the thickness measurement points. The quality assessment of new cultivator blades showed that their geometrical dimensions are identical on both sides, and the thickness change is 5.43 - 6.09 mm for MARATHON SERIES and 6.34 - 7.33 for 9.3 "TigerMate II. 14 measurements were carried out on each blade. Grasp width of new blades of two different manufacturers was 235mm and 234mm, respectively. Therefore, a blade was divided into three conditional zones from the center, through 39mm each. Geometrical dimensions are indicated by Roman numerals — the dimensions of wings, point tip, which corresponded to 7 dimensions. These measurements were necessary to assess wear rate.

Further, grasp width was measured on worn blades - size A (see Fig. 3), the differences of which can be noticed visually. By the difference of indications of new and out-of-service blades, they were judged on their wear, as well as on the analysis of their combination (superposition).

Results and Discussion

On the basis of the proposed technique, the cultivator blades of both foreign and domestic production were analyzed (Fig. 4 - 7). While operating the blade width of MARATHON SERIES remained almost unchanged, and 9.3 "TigerMate II decreased from 234mm to 227mm.

From the data obtained it follows that the cultivator blades do not wear evenly, the thickness in all areas of the analysis is different (Fig.4, 6). The dimensional characteristics of new blades are the same and symmetrical. After operation, they vary greatly (Fig.5, 7). This indicates that blades work in different conditions, soils and wear out unevenly. Skewness can be seen when fixing them on the rack of the cultivator. Some blades had visible abrasions (in the blade attachment zone) of the base metal, which indicated their long operating time and untimely replacement during maintenance or repair.

Wear of the cutting edges of cultivator blades is an irreversible process, during the interaction with the soil while operating. The size and nature of wear is determined, first of all, by stress pattern distribution on working surfaces of the cultivator blade [14].

To ensure cultivator blades durability, reduce the amount of their wear, it is necessary, on the one hand, to reduce the tendency to abrasive damage to the impact, and on the other hand, to improve the operational properties of the material by the technology and the type of applied reinforcing coatings.

Based on the experience of experts of Kharkiv Petro Vasylenko National Technical University of Agriculture, this may be most effective when using reinforcing with an optimal material and special modification. Experimental studies indicate that the greatest wear intensity of duckfoot sweep cultivator blades is typycal for the point tip. As moving away from it, the wear rate of the blade cutting edge decreases.

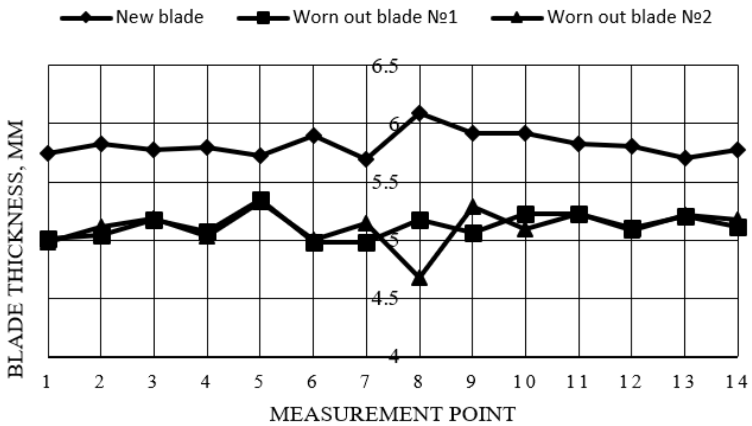


Fig. 4. Change in metal thickness of cultivator blades of MARATHON SERIES made in the USA while operating

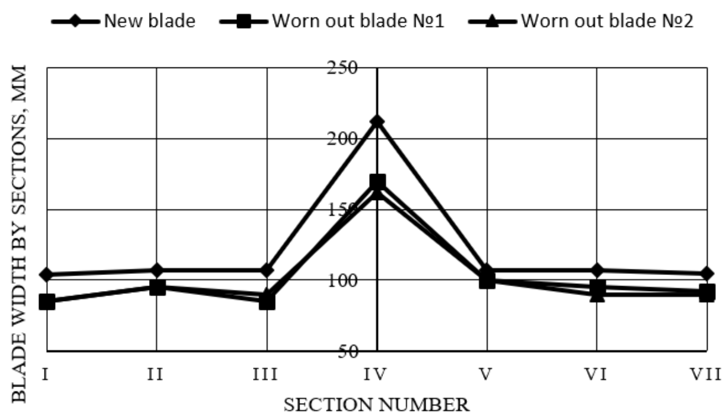


Fig. 5. Change of cultivator blades sizes of MARATHON SERIES made in the USA by sections (see. Fig. 3)

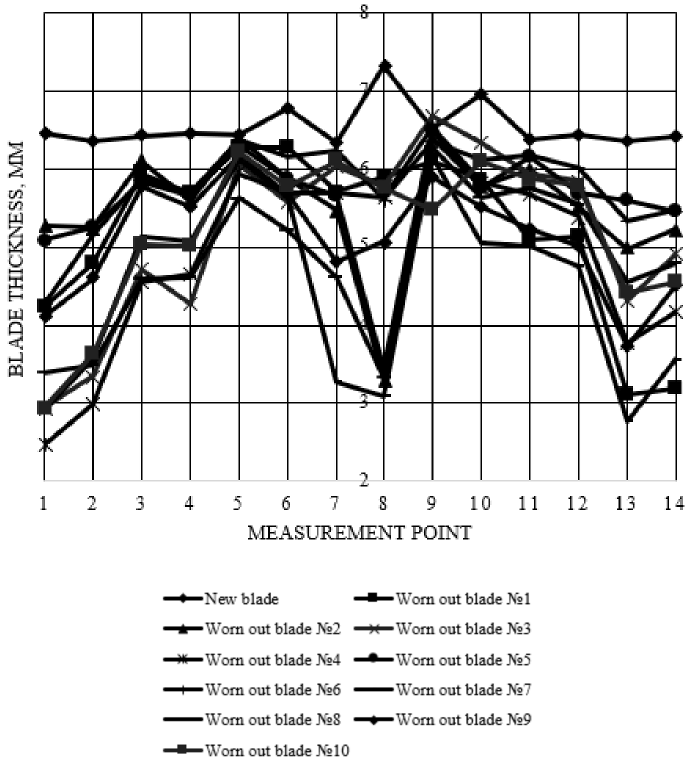


Fig. 6. Change in metal thickness of cultivator blades of 9.3 "TigerMate II made in Canada while operating (according to Fig. 3)

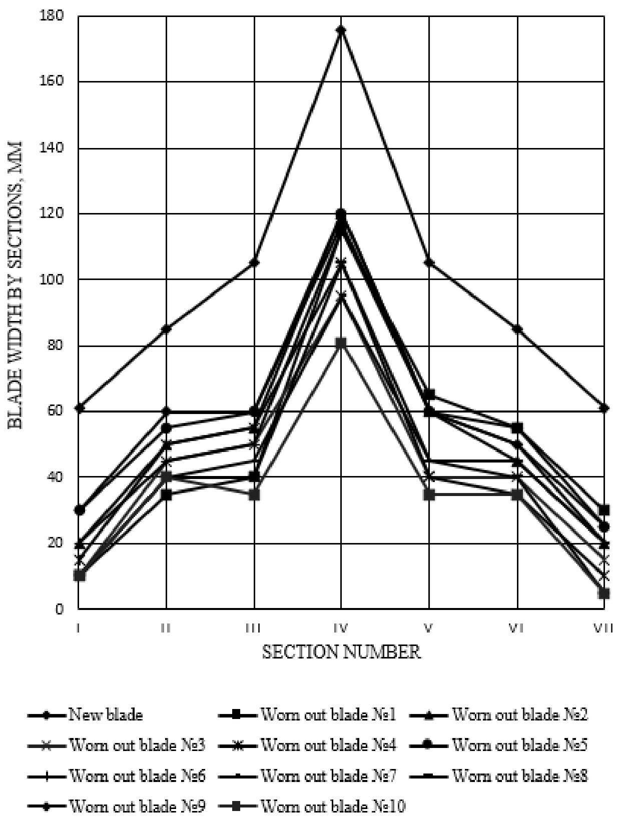


Fig.7. Changing cultivator blades sizes of 9.3 "TigerMate II made in Canada by sectional zones (according to Fig. 3)

The pattern of wear intensity change of the blade along the length of its cutting edge, presented in works [9, 10], has the form:

$$i = i_o m_i l^{-\frac{H_\mu X}{H_a}\sqrt{\frac{E_M S}{pT}l}}, \qquad (2)$$

where H_μ and H_a - hardness values of blade material and abrasive, respectively;
X – an empirical constant, taking into account optimal factors;
E_M – a coefficient of blade material elasticity;
S – an area of the blade working surface;
p – a specific load of the soil on the blade;
T – an operating time on one blade;
L –- a length of the section of reservoir;
i – a wear rate.

The proposed dependence of wear rate along the cutting edge length shows that the uneven wear of the cultivator blades can be explained by the varying pressure of the soil on different zones around the perimeter.

Having studied the nature of cultivator blades wear, a new method of their reinforcing along the working surface perimeter was proposed [15]. The method consists in surfacing wear-resistant stripes on the blade surface with the introduction of modifying agents with nano- and dispersed diamonds. Stripes on duckfoot sweep cultivator blade were formed according to Fig. 8, taking into account intensity and nature of its wear. According to the nature of wear, into point tip stripes with the size of 20 mm, and wings with the thickness of 12-15 mm with the distance of at least 10 mm between them will be formed by the reinforcing coating in order to prevent the length overlapping of heat-affected zones.

The optimal stripe sizes are determined from the conditions of the stress state formation during electrode surfacing, as well as by the coating quality and the tendency of the metal to damage during reinforcing. It is important to take into account, stresses appearing in the cutting edges and the transition zone of the blade base, wings while operating. Taking into account the maximum wear and wings deformation, reinforcing stripes in these zones were applied from the opposite surface relatively to the point tip (see Fig. 8).

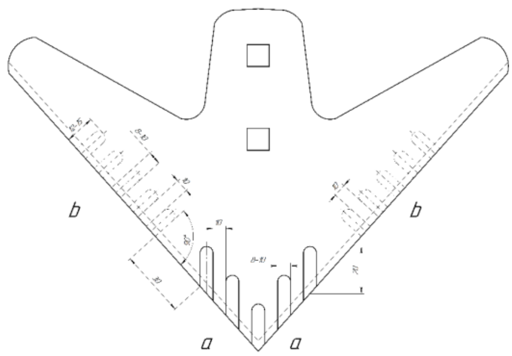
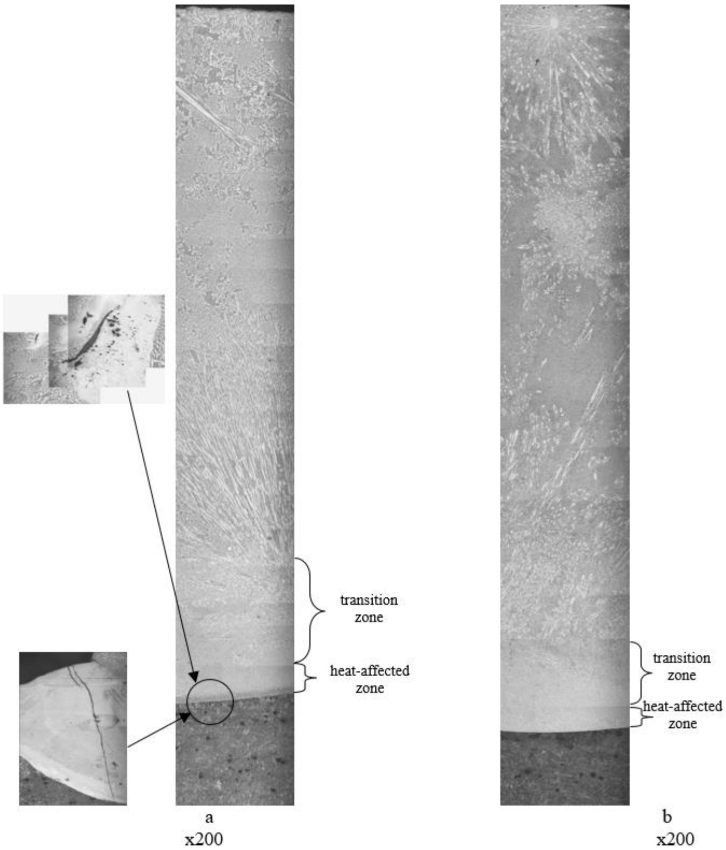


Fig.8. The scheme of reinforcing stripes surfacing on a duckfoot sweep cultivator blade surface (see Fig. 1,a, 2, a):
a – point tip;
b – wings

The possibility of using reinforcing surfacing to create stripes with T-620 carbide-containing electrode, which contains, %: 3,0 C, 2,2 Si, 1,2 Mn, 22,5 Cr, 0,7 Ti, 0,8 B, 0,03 S was studied. Such an electrode provides maximum penetration of the cultivator blade with the thickness of 6 mm to its depth up to 3 mm without defects when modifying it with a coating of non-magnetic component of the detonation charge obtained from the ammunition disposal. Such a charge, according to the chemical analysis, includes nano- and dispersed diamonds, and graphite (a small fraction) 3.37 - 3.43 % C, as well as copper (up to 3.14 %) and iron (up to 2.9 %) [16].

Previous studies [15] showed that the optimal share of the modifying additive is 6 - 8 %. For uniform entry into a liquid bath, it was used as an electrode coating. Current strength 160A and voltage 28V were used as the hardening parameters.

Application of the reinforcing technology to a small depth by stripes surfacing provides a high-quality reinforcing coating and fusion zone with minimal heat input due to the micro-refrigerators creation - inclusions of dispersed diamonds that do not dissolve in the liquid bath, but significantly reduce its temperature (by 250-300 °C). This reduces the grain size by 20%, the heat-affected zone by 40% and stress, and also increases the anisotropy of the structure in the applied reinforcing stripes not only on the cutting edge, but also in the base metal. The anisotropy of the structure in such a built-up metal is 0.95-0.97. These properties provide the operational durability increase due to the absence of the tendency of the metal to crack formation in the heat-affected zone of surfacing when stripes are applied.



a **b**

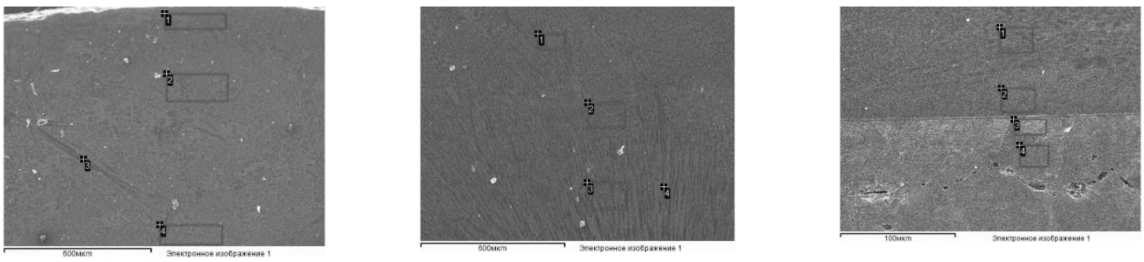
Fig.9. Microstructure over the section of samples:
a - surfacing with T-620 electrode;
b - surfacing with T-620 electrode
with non-magnetic fraction modification of the detonation charge

Fig. 9 comparatively shows the formed structures during surfacing without modifying by secondary charge (a), which were accompanied by crack formation in the varying thickness blade-base area, as well as in another blade part, and (b) using a modifying agent, which was previously applied on the surface of electrodes ∅ 4,0 mm with charge proportion of 6.0 - 8.0 % [15]. When forming stripes, a current of 150 - 180A was used, the deposition rate was 17 - 19 m/h.

Besides identified defects (pores, cavities and cracks), it should be noted that in the area of reinforcing stripes application a more heterogeneous structure is formed with the formation of zones of coarse, thin, and extended carbide sockets near the fusion boundary, which is characterized by increased microhardness.

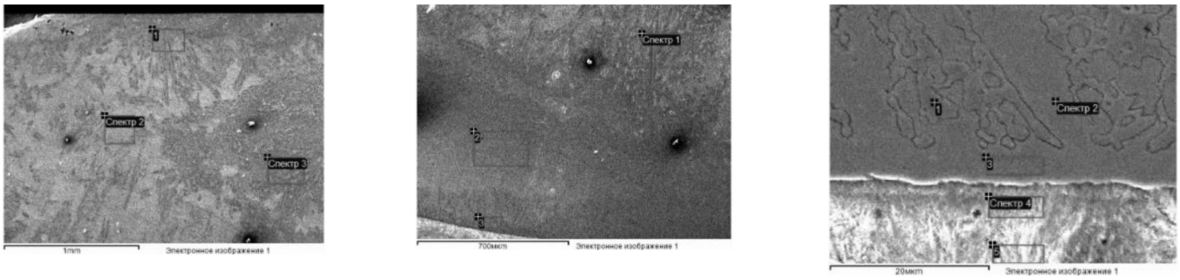
When modifying, such carbide sockets are more evenly distributed in the metal matrix, and they differ in structure. Instead of extended thin inclusions, they are fragmented, what contributes to the formation of a more homogeneous structure, less stress state of the transition zone, as well as its length decrease. In this transition layer, there are no defects at all.

Distribution of chemical components along the depth of the surfaced stripe in accordance with two options - without and with the use of a modifying agent was locally estimated by X-ray electron probe analysis (XREPA) (Fig. 10 and 11, Table 1 and 2).



a **b** **c**

Fig.10. Electronic photographs of the structure of the surfaced stripes with T-620 electrode indicating XREPA zones:
a - surfacing surface;
b - middle;
c - heat-affected zone



a b c

Fig.11. Electronic photographs of the structure of the surfaced stripes with T-620 electrode with a non-magnetic fraction modification of the detonation charge indicating XREPA zones:
a - surfacing surface; b - middle; c - heat-affected zone

When modifying metal surfacing in the stripe, the temperature of the liquid bath decreases (the presence of micro-refrigerators - diamonds) and the crystallization conditions change [17]. This is accompanied by increase in the average share of the carbide phase by 27 % in the upper zone, in the middle by – 32 % and transitional – 70 %. Besides that, the homogeneity of the distribution of carbon-bearing phases in surfaced stripes is more uniform across the section during the modification with the secondary charge. Thus, during conventional surfacing, carbon concentration in the upper zone varies within 2.8 %, the middle is 1.83 %, and the transition one is 1.64 %. In the case of modification, there is a large homogeneity in the distribution of this component in various zones. This corresponds to the achieved microhardness level. With the conventional method of surfacing there is a significant proportion of oxygen in all zones of analysis up to 1.6 - 3.39 %. When modifying with the secondary charge (see Table 2), this component was singly detected only in the upper zone of the stripe (2.28 %).

As for the distribution of Mn, Si, Mo components, they are close in concentration in comparable variants. Regarding the proportion of iron, its average value is 8.4 % more when modifying, and in the upper and middle zones it differs even more significantly - by 14.5 %. The observed can be explained by the formation in these zones of a larger amount of cementite-type carbides.

Table 1

XREPA data on the distribution of chemical elements over the section of the deposited stripes with T-620 electrode, %

Surface

Spectrum	C	O	Al	Si	Cr	Mn	Fe	Zr	Mo
1	8.71	3.15	0.51	1.69	22.24	5.38	55.47	0.34	2.50
2	8.91	2.78	0.19	1.48	24.05	4.96	54.61	0.86	2.15
3	10.51	-	-	0.05	42.71	5.49	39.47	-	1.77
4	7.71	2.52	0.17	1.60	23.35	5.34	56.83	0.84	1.64
Max	10.51	3.15	0.51	1.69	42.71	5.49	56.83	0.86	2.50
Min	7.71	2.52	0.17	0.05	22.24	4.96	39.47	0.34	1.64

Middle

Spectrum	C	O	Al	Si	Ca	Cr	Mn	Fe	Zr	Mo
1	8.05	2.42	0.23	1.53	0.18	24.24	5.75	54.81	0.81	1.98
2	7.60	2.37	0.29	1.60		22.85	5.55	57.03	0.36	2.37
3	7.69	1.60	0.29	1.55	0.09	24.04	5.53	56.86	0.34	2.02
4	9.43					42.95	5.19	41.00		1.43
Max	9.43	2.42	0.29	1.60	0.18	42.95	5.75	57.03	0.81	2.37
Min	7.60	1.60	0.23	1.53	0.09	22.85	5.19	41.00	0.34	1.43

Transition zone

Spectrum	C	O	Al	Si	Cr	Mn	Fe	Zr	Mo
1	7.14		0.26	1.60	21.96	5.35	61.26	0.29	2.14
2	7.01	2.30	-	1.27	13.91	3.90	70.29	-	1.32
3	6.65	3.39	0.17	0.19	0.28	0.99	88.32	-	-
4	5.55	2.11	-	0.17	-	0.92	91.24	-	-
Max	7.14	3.39	0.26	1.60	21.96	5.35	91.24	0.29	2.14
Min	5.55	2.11	0.17	0.17	0.28	0.92	61.26	0.29	1.32

Table 2

XREPA data on the distribution of chemical elements over the section of the deposited stripes with T-620 electrode with modification of a non-magnetic fraction of the detonation charge, %

Surface

Spectrum	C	O	Al	Si	Cr	Mn	Fe	Mo
1	12.98	2.28	0.22	1.17	17.05	3.90	61.12	1.27
2	10.78			1.28	18.19	4.12	64.15	1.47
3	14.06		0.59	1.37	19.13	4.23	58.61	2.01
Max	14.06	2.28	0.59	1.37	19.13	4.23	64.15	2.01
Min	10.78	2.28	0.22	1.17	17.05	3.90	58.61	1.27

Middle

Spectrum	C	Al	Si	Cr	Mn	Fe	Mo
1	13.12		1.39	18.58	4.19	61.07	1.65
2	9.28	0.47	1.45	17.06	3.79	66.54	1.41
3	9.23		1.30	15.47	3.60	68.80	1.60
Max	13.12	0.47	1.45	18.58	4.19	68.80	1.65
Min	9.23	0.47	1.30	15.47	3.60	61.07	1.41

Transition zone

Spectrum	C	Si	Cr	Mn	Fe	Mo
1	13.61	0.55	23.14	3.66	57.77	1.27
2	10.78	1.39	7.88	2.72	77.24	
3	9.82	1.20	16.30	3.28	68.62	0.78
4	8.06	0.98	5.79	2.28	82.89	
5	11.20	0.24	0.46	1.11	86.98	
Max	13.61	1.39	23.14	3.66	86.98	1.27
Min	8.06	0.24	0.46	1.11	57.77	0.78

Chromium distribution over the three analyzed zones is 2.2 times more uniform when using modifying with stripes application by surfacing, which is achieved by carbide phases crushing during crystallization.

Insignificant tendency of Al increase during the modification can be explained by the fact that this component is part of the detonation charge. It was revealed that its share in different surfacing zones (upper, middle) varies within 0.17-0.51 % at conventional stripes surfacing and - within 0.22-0.59 % in the case of modifying with a secondary charge.

The absence of difference in the content of Al and Si components can be related to the concentration change of these components, taking into account that with conventional application of stripes by surfacing, base metal inclusions emerge to the coverage area, and when modifying, they are a part of the modifier and their share in it is not stable.

Wearing tests were carried out on SMT-1 friction machine at State Enterprise V.A. Malyshev Plant.

The relative wear resistance of various reinforcing methods of parts surfaces was carried out and evaluated according to three variants [17]:

1 - source material of a cultivator blade steel 65G;

2 - surfacing with T-620 electrode with modification by a non-magnetic fraction of the detonation charge;

3 - surfacing with T-620 electrode.

Tests were carried out according to “disc-block” scheme. Tests of samples in the abrasive medium of quartz sand without lubrication were carried out according to Brinell scheme. Samples 10x10 mm in size, cut from the surfacing zone and processed on a surface grinder with a load of 5 kg, were subjected to testing. Counterbody - PTFE-4 – Fluoroplastic. In this test, fluoroplastic was used as a body to hold abrasive in the friction area. The sand from the Staroverovsky deposit (Ukraine) with a fraction of 0.25-0.4 mm was used as an abrasive. Before testing, the prepared samples (blocks, discs) were washed, marked, weighed on a WA-200 scales.

Test results are shown in Table. 3. The friction path was 100 m.

Table 3

Abrasion tests

No./no.	Reinforcing option	Wear, g
1	Source material of cultivator blade steel 65G	0.0145
2	Surfacing with T-620 electrode	0.0090
3	Surfacing with T-620 electrode with modification by a non-magnetic fraction of the detonation charge	0.0044

The proposed reinforcing method of cultivator blades is recommended for stable operation of equipment by minimizing the creation of local stresses, which ensures the absence of defects, as well as while operating - improvement of the working tool stability (excludes the deformation of the wings) and in 3 times increases wear resistance comparing to the product source material or reinforcing without modification.

Experiments were carried out by comparing 81 pieces of two types of cultivator blades in one installation of the Tiger Mate II cultivator - 66 pieces without hardening and 15 hardened pieces, proposed by the method, which showed on average that their wear is much less, regardless of their location and decreases 2.3 times, which almost corresponds to bench tests. The tests were carried out in PE "Agrarian Investments" of the Sumy region, Ukraine.

Conclusions

1. A new solution is presented for a constructive approach to reinforcing cultivator blades without deformation and with the use of secondary raw material modifi-cation from the ammunition disposal with a non-magnetic fraction of the detona-tion charge, which makes it possible to use a high-carbon alloyed electrode metal.

2. As a result of the carried out research, a new reinforcing method of cultivator blades was developed and proposed. The method consists in applying reinforc-ing stripes on the point tip from the front side of the blade and on its wings from the back. According to the analysis of wear processes, it is optimal to apply re-inforcing stripes on the point tip of 20 mm in size and 12 to 15 mm on the wings with a distance of at least 10 mm between them to prevent overlapping of the heat-affected zones.

3. When reinforcing stripes are surfaced with carbide-containing T-620 electrode, research were carried out on the possibility of using for modification non-magnetic fraction of the detonation charge from the ammunition disposal in the form of electrode coating. To control liquid bath temperature, the proportion of introduced modifier was optimized. It was found out that this combination of blade materials and reinforcing stripes allows to reduce heat input, improve sur-facing quality (ensure coarse carbides crushing), increase hardness and wear resistance by 2 and 3 times comparing to the initial state and reinforcing without modifying additions, respectively, and also to eliminate defects formation when reinforcing quite a thin working tool.

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Скобло Т.С., Рибалко І.М., Нанка О.В., Сайчук О.В. Оцінка зносу стрілчастих лап культиватора і технологія їх зміцнення.

В останні роки особливе місце в наукових досягненнях займають розробки, пов'язані зі створенням нових напрямків з використанням нанотехнологій. Вони розвиваються і широко використовуються у фізиці, хімії, біології, електроніці, медицині, харчовому виробництві і значно меншою мірою в машинобудуванні. Це пов'язано з тим, що до деталей і виробів, що використовуються в машинобудуванні, пред'являються різні вимоги, вони мають складну форму, виготовляються з відмінних матеріалів, способів виробництва, термообробки. В процесі експлуатації їх робочий шар піддається деградації з істотною зміною структури і їх зміцнення з використанням нанопокриттів може виявитися, як в технічному, так економічному аспектах неефективним. У цьому випадку доцільним може бути тільки конкретне рішення, яке визначається всебічними дослідженнями з виявленням основних факторів пошкоджуваності деталей в конкретних умовах виробництва і експлуатації. Крім того, в ряді випадків для зміцнення, ремонту та відновлення деталей доцільно використовувати методи наплавлення з введенням модифікують присадок в рідку ванну при кристалізації. До числа таких присадок слід віднести нано- та дисперсні алмази, які дозволяють коригувати температурні параметри кристалізації, величину зерна, рівень напружень. Такий підхід дозволяє використовувати і високолеговані, високовуглецеві електроди навіть для тонкостінних виробів із сталей і чавунів. В цьому випадку присадка шихти з алмазною фракцією відіграє роль мікрохолодильників, які суттєво змінюють температурний інтервал кристалізації. Важливим є визначити оптимальну дозу введення такого модифікатора та забезпечити рівномірний розподіл компонентів у покритті. Представлена робота присвячена розробці нової технології зміцнення металу стрілчастих лап культиватора нано- та дисперсними домішками алмазів, які входять до складу детонаційної шихти від утилізації боєприпасів. В даний час в сільському господарстві для обробки ґрунту використовується велика кількість ґрунтообробних знарядь, з робочими органами яких є стрілчасті лапи. Вони експлуатуються в умовах впливу абразивних частинок, та це супроводжується їх інтенсивним зносом з відповідною зміною геометричних розмірів основних робочих поверхонь. Зношені стрілчасті лапи значно знижують ефективність і якість виконуваних робіт. Проведено аналіз ефективного вибору наплавлювального матеріалу для зміцнення та підвищення їх працездатності і оцінено характер зносу, щоб виявити і зони максимальної пошкоджуваності, а також визначити оптимальний спосіб зміцнення. Відомо, що для відновлювального наплавлення ґрунтообробних знарядь застосовують електроди Т-590, Т-620. Встановлено, що наплавлення тонкостінних деталей супроводжується меншим тепловідводом та вони в ряді випадків проплавляються з формуванням дефектів. Для його зниження вводили не магнітну фракцію детонаційної шихти від утилізації боєприпасів у вигляді модифікування електрода, що забезпечувало рівномірний розподіл компонентів у покритті. Методом мікрорентгеноспектрального аналізу оцінено особливості структуроутворення і розподілу компонентів при такій технології зміцнення по перетину покриття. Встановлено, що даний спосіб зміцнення знижує тепловкладення й підвищує мікротвердість і зносостійкість наплавленого покриття, зменшує перехідну зону й термічного впливу. Рекомендований спосіб зміцнення металу нових лап культиватора полягає в нанесенні смуг на носок і крила лап. На основі характеру зносу обґрунтовано доцільність нанесення смуг на носок лапи культиватора з лицьового боку, а на крилах - з тильного. Наведено оптимальні геометричні розміри зміцнюючих смуг і їх розташування на лапі, що дозволяє мінімізувати створення локальних напружень і підвищення зносостійкості.

Ключові слова: лапа культиватора, наплавлення, детонаційна шихта, смуги, тепловкладення, модифікування, структуроутворення, нано- та дисперсні алмази.

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Influence of cathode and anode processes on tribocorrosion of aluminium alloy AA2024 in acid rain

M. Khoma[1], V. Vynar[1], Ch.Vasyliv[1*], A. Dykha[2], Yu. Kovalchyk[3]

[1]Karpenko Physico-Mechanical Institute of the NAS of Ukraine,
[2]Khmelnytskyi National University
[3]Lviv National Agrarian University
**E-mail: chrystyna.vasyliv@gmail.com*

Abstract

The nature of cathodic processes during the frictional interaction of aluminum alloy with ball corundum in the conditions of reciprocating motion has been studied. Under conditions of anodic polarization under conditions of friction, corrosion processes are activated and their speed during friction increases many times. The potential on the surface of the alloy under acid rain shifts sharply in the negative direction. Changes in the tribopotential and coefficient of friction are characterized by a gradual shift in values at the initial stage of research. The oxide film is formed on the metal surface in neutral and acidic environments. The service life of the film is increased due to electrochemical protection during cathodic polarization at the electrode potential of pure alloy without oxide film. It is proved that polarization changes the life of the film in the initial stages and the loss of material and the coefficient of friction during the entire test period. It is established that the nature of surface fracture also changes as a result of application of the polarization potential during friction. The largest surface damage is observed during anodic polarization.

Keywords: polarization, corrosion, damage, secondary films, friction, cathode potential

Introduction

The destruction of materials in a result of tribocorrosion occurs in many industries: processing, energy, chemical and others [1]. Friction units operating in active media are the subjects of destruction. In such systems, wear can occur from the flow of liquids, collisions of particles or contact of solids. Therefore, the study of tribocorrosion processes and the influence of various factors on them is an urgent scientific and technical problem. Electrochemical methods are important to solve them [2 - 7].

There are two interrelated areas in the field of research of electrochemical processes at the friction of metals: the use of electrochemical parameters to obtain information about contact processes and an attempt to control friction and wear of materials using electrochemical methods [1]. The second direction - active intervention in the electrochemical processes on the friction contact - has received much less development than the first, although it seems quite promising. One of the control methods is the polarization of the friction system from an external source [8]. The method consists in the fact that the systems with the help of an external source of polarization is shifted to a certain area for the processes of friction and wear, and is maintained at a given level during the operation of the friction pair. Polarization of the friction system pursues various goals: to reduce surface energy, to improve the wettability and adsorption of environmental components, and others. Some cases of this method are anodic and cathodic protections, which change the corrosion-mechanical processes and the formation and destruction of secondary structures.

The purpose of the work − to study the frictional interaction of tribotechnical pairs: alloy AA2024 - corundum indenter, interacting in an acidic environment under conditions of cathodic and anodic polarization.

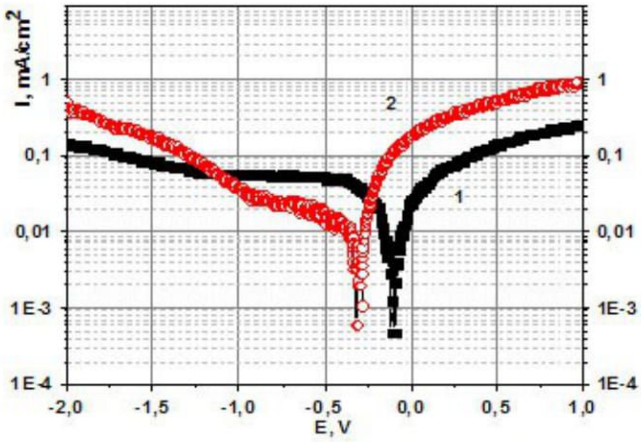
Materials and research methodology

Tribocorrosion studies of aluminum alloy AA2024 (size of samples 50 × 40 × 5 mm) were performed on a reversible friction test plant [5] according to the scheme "ball - plane". The load on the ceramic ball was 1 N, the length of the friction track - 24 mm, the speed of movement - 1.6 mm/s, friction time 20 min. During the tribocorrosion tests, the change in the friction moment was recorded and the polarization was set using the PI-50-1.1 potentiostat. A saturated silver chloride reference electrode and an auxiliary platinum electrode were used. The kinetics of changes in the measuring parameters were recorded by an analog-digital device by using a personal computer with a measurement step of 0.25 s. The working medium was acid rain [7] with a pH=4.5, reduced by the addition of Na_2CO_3.

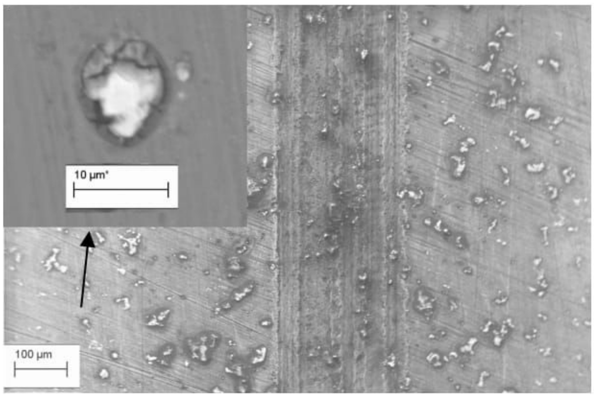
A scanning electron microscope EVO-40XVP (Carl Zeiss) with a system of micro-X-ray spectral analysis using an energy dispersion spectrometer INCA ENERGY 350 was used to study the surface of the aluminum alloy after corrosion mechanical wear.

Analysis of research results

It is established (Fig. 1, a) that the character of cathode processes changes during the frictional interaction of the AA2024 alloy with the corundum ball in the acid rain during the reciprocating motion of the indenter. There is an oscillation of corrosion currents in the polarization curve from the corrosion potential to -1.2 V (potential of freshly renewed surface) because there is a local change of cathode-anode processes on the deformed surface. It indicates the formation and destruction of secondary structures. At a potential below -1.2 V, hydrogen depolarization blocks the formation of films due to near-surface alkalization of the interaction zone, which intensifies the rate of chemical corrosion. This is evidenced by the dissolution in the contact zone (Fig. 2, b), especially intense local corrosion at the sites of intermetallic compounds.



a



b

Fig. 1. Polarization curves of AA2024 alloy (a) and its damage (b) during tribocorrosion at a potential of -1.6 V in acid rain:
1 – without load; 2 – during friction (P = 1 N, counter body: ball Al_2O_3)

Under anodic polarization, both in stationary conditions and under frictional interaction, corrosion processes are activated, and their speed during friction increases 5 times.

Tribocorrosion studies have shown that potential on the surface of the alloy AA2024 in acid rain is -0,520 V without applying a load. Its potential shifts sharply to the negative side and becomes -0,770 V with the beginning of mechanical activation of the surface by a moving indenter. The average value of the friction coefficient gradually increases with the beginning of research and its value was established at the level of ~ 0,43 after a stage of running-in. Changes of the tribopotential and the coefficient of friction are characterized by a gradual shift of values at the initial stage of research. The oxide film is formed on the metal surface in neutral and acidic environments [4]. This film contacts with the indenter, destructs and is removed from friction zones during the friction.

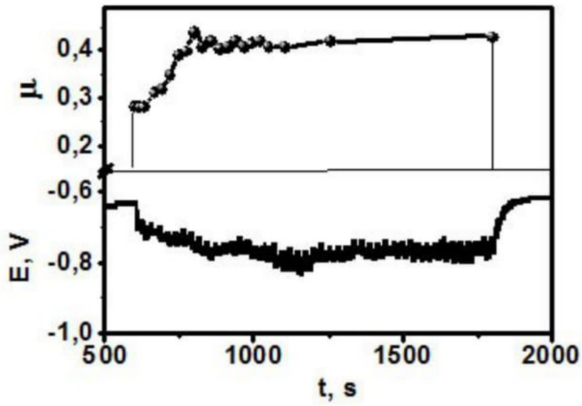
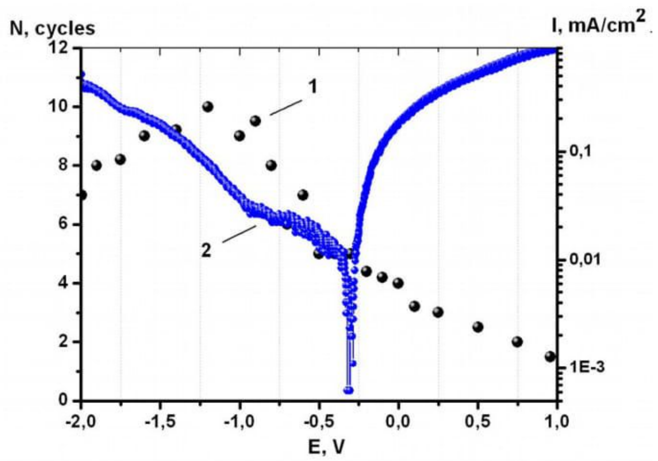
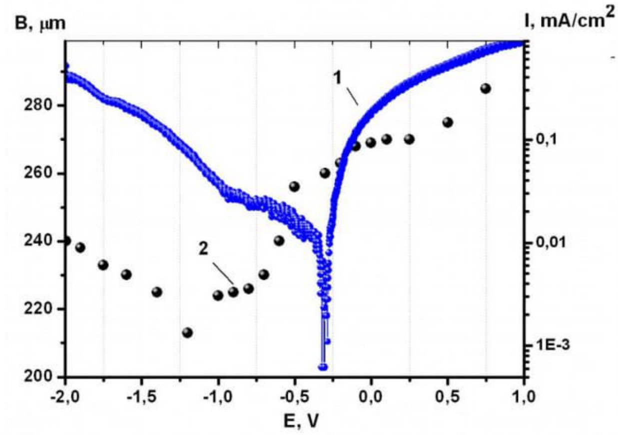


Fig. 2. Time dependences of friction coefficient and corrosion potential of aluminum alloy AA2024 during tribocorrosion studies in acid rain solution

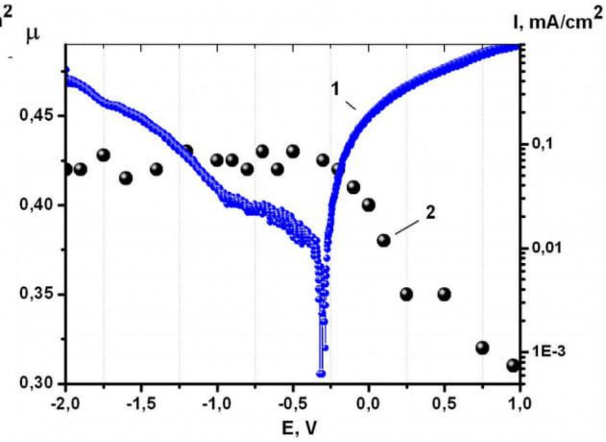
It was found (Fig. 3 a) that, this film is destroyed in 6 passes of the indenter without the potential applying. The change of the polarization potential from stationary potential in the cathode and anode sides significantly changes the lifetime of the film. The lifetime of the film increases due to electrochemical protection at cathodic polarization in the range of -0.700…-1.200 V. It is most evident at the electrode potential of pure alloy AA2024 without oxide film (-1.200 V). The destruction of the film intensifies as the potential increases in the negative direction from the potential -1.200 V. The reason for this is the near surface alkalinization of the environment due to the increase in the rate of hydrogen depolarization [10]. When level of polarization increases, the chemical corrosion intensifies, and the destruction increases. Friction during anodic polarization significantly accelerates processes of electrochemical corrosion and intensifies the destruction of the film. Damage of film occurs without the frictional interaction at potentials of 0.750… 1.000 V and the indenter already removes its remnants from the contact zone. Polarization changes the lifetime of the film in the initial stages of tribocorrosion tests. Also it changes the material loss and friction coefficient for the entire period of tribocorrosion tests (Fig. 3 b, c). Cathodic polarization reduces material loss. So the width of the track on the surface without polarization is 230 μm and it is reduced to 225 μm with a potential shift in the negative direction.



a



b

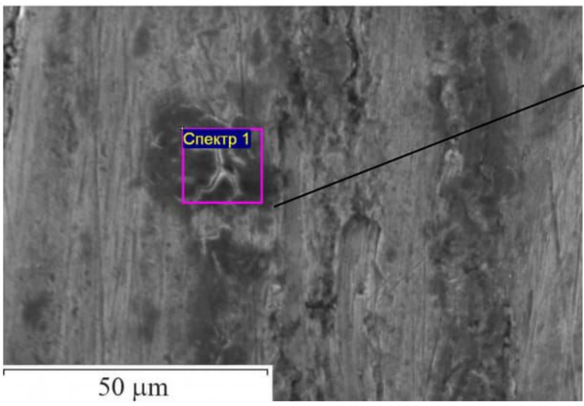


c

Fig. 3. Dependence of the rate of destruction of the oxide film (a), material loss (b) and friction coefficient (c) on the polarization potential of the alloy AA2024 by friction in acid rain in contact with a ceramic ball (1N):
1 – polarization curve of AA2024 alloy for tribocorrosion;
2 – parameters:
a – destruction of the film;
b – the width of the friction track; c - coefficient of friction

The smallest material losses are observed at a potential of -1.200 V, due to the maximum inhibition of corrosion processes, the track width is 212 μm. Shifting the potential to more negative values, as in the case of natural oxide film (Fig. 3 a), leads to alkalinization of the environment and intensification of corrosion processes. Material losses increased due to corrosion-mechanical wear. Anode polarization, which is only 0.100 V relative to the steady-state potential, increases the width of the wear track by 20 μm. With a shift of the polarization potential to a more positive side, the loss increases the material loss and at a polarization potential of +1,000 V is 45 % compared to an alloy without polarization.

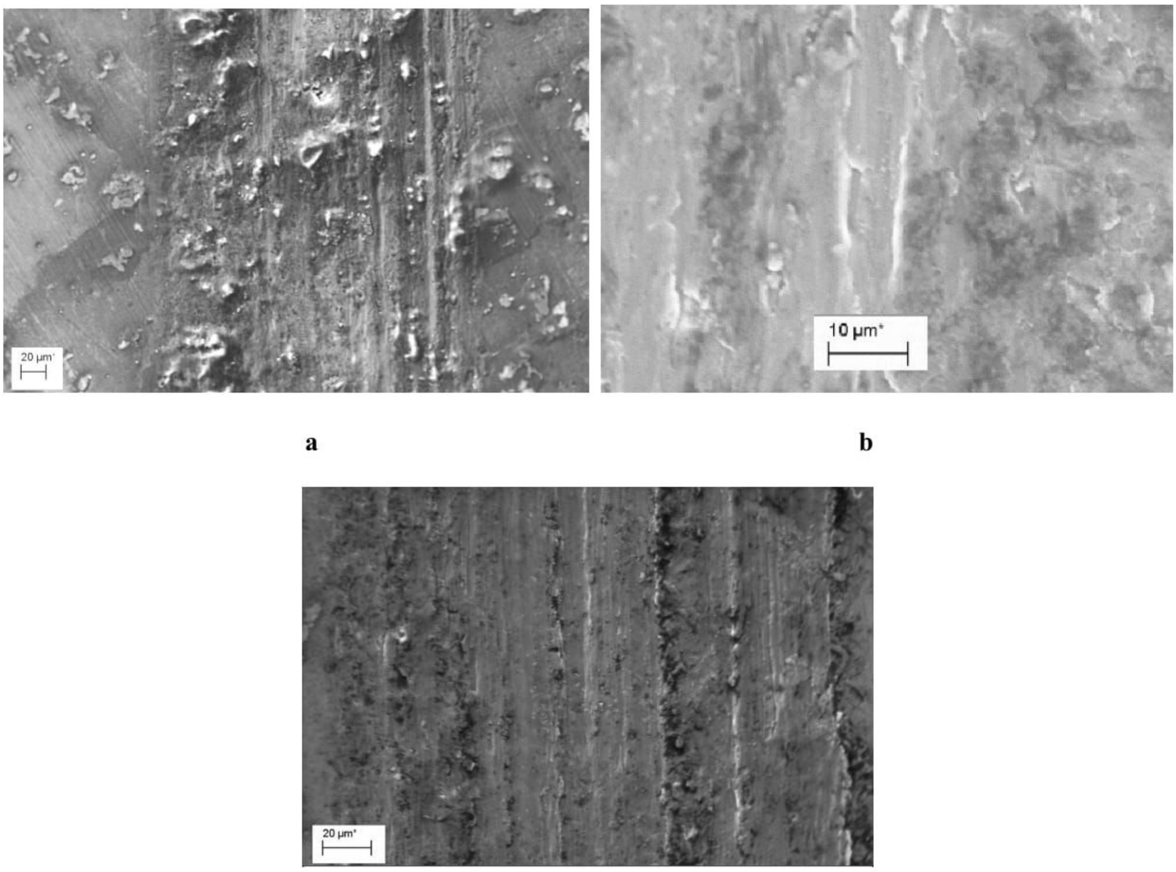
It is established that the dependence of the friction coefficient on the polarization potential for tribocorrosion has the opposite character to the material loss. It is to some extent abnormal for most tribological processes. Cathodic polarization does not change the value of the coefficient of friction, the increase occurs only at the potentials -0.120 V (maximal inhibition of corrosion processes). Anodic polarization intensifies corrosion processes, accelerates the formation of secondary structures, which consist mainly of Al (63.2 mass. %) and O (32.19 mass %) (Fig. 4). It reduces adhesion interaction of friction surfaces. So, with increasing polarization potential, the coefficient of friction decreases from 0.43 to 0.32 at a potential of 1.000 V.



Element	Mass. %	At.%
O K	32.19	45.27
Mg K	1.17	1.08
Al K	62.30	51.95
S K	0.24	0.17
Mn K	0.37	0.15
Fe K	1.29	0.52
Cu K	2.44	0.86

Fig. 4. Chemical composition of secondary structures, which are formed by anodic polarization (0.100 V) of AA2024 alloy during tribocorrosion

The nature of the surface destruction also changes in a result of the application of the polarization potential during friction (Fig. 1b and Fig. 5). Thus, the greatest surface damage is observed during anodic polarization. For example, there are etches and products of the combined action of corrosion and friction - especially active local corrosion - at a potential of 0.500 V on the surface (Fig. 5a). The appearance of microcutting elements is found on the material without the application of polarization (Fig. 5, b). Under these conditions the rate of secondary structures formation decreases compared to anodic polarization and the adhesive interaction between the contact surfaces increases. The surface damage decreases in the case of the polarization potentials shift in the cathode direction, as electrochemical corrosion is inhibited, but the role of chemical dissolution increases. There is a change in the mechanism of corrosion, and therefore the mechanism of friction at the potential of the freshly renewed surface (-1.200V). At this potential, electrochemical corrosion is practically blocked, but chemical corrosion begins to intensify due to near-surface alkalinization of the environment.



a **b**

c

Fig. 5. Topography of the surface of AA2024 alloy after tribocorrosion studies in acid rain at different potentials of polarization:
a – polarization at +0.500 V;
b – without polarization;
c -- polarization at -1.200 V

As the rate of hydrogen depolarization increases, the concentration of hydrogen in the near-surface layer increases and the pH of the solution changes intensively. It is manifested in the local etching of intermetallic inclusions in the contact zone (Fig. 1b).

Thus, depending on the level of cathodic and anodic polarization, the intensity of destruction of the AA2024 alloy during tribocorrosion in pair with corundum counter body changes.

Conclusions

1. The influence of external cathodic and anodic polarization on tribocorrosion of AA2024 alloy paired with a ceramic ball in acid rain has been studied.

2. The dual influence of cathodic polarization on the tribocorrosion of AA2024 alloy is established. The destruction of metal is inhibited at the potentials below the potentials of the freshly renewed surface. It is due to the reduction of the corrosion rate. Above this potential, corrosion-mechanical wear intensifies due to alkalization of the near-electrode layer of the electrolyte in a result of hydrogen depolarization. Changes in the coefficient of friction are insignificant.

3. It is shown that the anodic polarization intensifies the formation of secondary structures. As a result, there is an increase in losses of materials and the decrease of friction coefficient. It indicates the lubrication properties of products that are intensively removed from the friction zone.

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Хома М., Винар В., Х. Василів, Ковальчик Ю. Вплив катодних і анодних процесів на трибокорозію алюмінієвого сплаву АА2024 у кислотному дощі.

Досліджено характер катодних процесів під час фрикційної взаємодії алюмінієвого сплаву із кульковим корундом в умовах зворотно-поступального руху. В умовах анодної поляризації в умовах тертя активізуються процеси корозії і їх швидкість під час тертя збільшується в рази. Потенціал на поверхні сплаву під кислотними дощами різко зміщується в негативну сторону. Зміни трибопотенціалу та коефіцієнта тертя характеризуються поступовим зміщенням значень на початковому етапі досліджень. Оксидна плівка утворюється на поверхні металу в нейтральних та кислих середовищах. Термін служби плівки збільшується за рахунок електрохімічного захисту при катодній поляризації при електродному потенціалі чистого сплаву без оксидної плівки. Доведено, що поляризація змінює час життя плівки на початкових етапах та втрати матеріалу та коефіцієнт тертя протягом усього періоду випробувань. Встановлено, що характер поверхневого руйнування також змінюється в результаті застосування потенціалу поляризації під час тертя. Найбільші поверхневі пошкодження спостерігаються під час анодної поляризації.

Ключові слова: поляризація, корозія, пошкодження, вторинні плівки, тертя, катодний потенціал

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Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

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Structural identification of the mathematical model of the functioning of tribosystems under conditions of boundary lubrication

A.V. Voitov

Kharkiv Petro Vasylenko National Technical University of Agriculture, Kharkiv, Ukraine
E-mail:: K1kavoitov@gmail.com

Abstract

In the work, a methodological approach to obtaining mathematical models was further developed, which describe the functioning of tribosystems in stationary and transient modes under boundary lubrication conditions.

The structural identification of the tribosystem as an object of modeling the functioning of tribosystems in the conditions of boundary lubrication is performed. It is established that the operation of tribosystems is described by a third-order differential equation and, in contrast to the known ones, takes into account the function of changing the quality factor of the tribosystem during running-in. It is shown that the nature of the functioning of tribosystems under conditions of ultimate lubrication depends on the gain and time constants included in the differential equation.

It is shown that the coefficient K_1 takes into account the degree of influence of the input signal (load, sliding speed, tribological characteristics of the lubricating medium), on the value of the output signal (quality factor of the tribosystem). Coefficient K_2 takes into account the magnitude of the change of the output parameters (volumetric wear rate and friction coefficient) when changing the values of the input parameters (load, sliding speed, quality factor of the tribosystem. Coefficient K_3 takes into account the degree of influence of the input signal on the restructuring of the material structure in the surface layers of the triboelements.

The time constants of the tribosystem characterize the inertia of the processes occurring in the tribosystem, during running-in, or during changes in operating modes. Increasing the time constants makes the process less susceptible to changes in the input signal, the running-in process increases over time, and the tribosystem becomes insensitive to small changes in load and slip speed. Conversely, the reduction of time constants makes the tribosystem sensitive to any external changes.

Key words: tribosystem; mathematical model; differential equations; structural identification; gain; time constant; boundary lubrication; quality factor of tribosystem; dissipation speed.

Introduction

Recently, methods of calculating and modeling the processes of friction and wear in tribosystems of machines and mechanisms have been actively developing, which makes it possible to significantly reduce costs in the process of designing and fine-tuning new structures. Difficulties that arise in the development of such models are associated with the choice of parameters that affect the process under study.

The task of developing mathematical models of stationary and transient processes in tribosystems under boundary lubrication conditions is related to the problems of stochastic modeling, since initial data for modeling (tribosystem design, lubricating medium, materials from which triboelements are made, roughness of friction surfaces, load-speed range of operation, etc.), are random functions. Analysis of models of stationary processes in tribosystems shows that there is a large error in modeling the wear rate, up to 12,8 % and coefficient of friction, up to 14,0 %. Such a scatter of data in measurements can be explained by the presence of an oscillatory process of the wear rate and the coefficient of friction during the operation of the tribosystem, as well as by the ambiguity of the choice of input parameters for modeling.

Literature review

In work [1] the analysis of the current state of the methods for calculating wear and forecasting the resource is given and the conclusion is drawn, that analytical methods do not allow taking into account the dynamics of changing the operating modes of the contact, and numerical methods seem to be promising. The author of the work proposed to describe the wear by an array of vectors of probabilities of the wear values of discrete points of the surface, which are modeled by non-stationary random functions of the Markov type, and wear is estimated by the mathematical expectation of the probability of finding surface elements in a certain state. The shape of the worn surface is determined using a cubic spline approximation of the mathematical expectation of wear at the points of location of the modeled elements.

In work [2] the physical mechanisms of formation and transformation of corpuscular-vortex perturbations in the contact of the tribosystem, which are based on the quantum-mechanical exchange mechanism of interaction, are considered. The presence of a contact gap determines the generation of pairs of quasiparticles-perturbations, stabilized by wavelength and frequency. It is established in the work that the internal instability and collapse processes in such a system of perturbations lead to defect formation in the material of the tribosystem and underlie the emergency modes of friction.

In the works [3, 4] performed analysis of the strength and durability of the surface layer material by friction. The authors propose to take into account the presence of two areas of accumulation of damage and the type of mechanism of destruction: the area of multicycle fatigue and a layer of debris. Methods for estimating the parameters of the durability model for the region of multicycle fatigue are proposed. The connection between the stress-strain state and the fatigue strength characteristics of the material with the characteristics of the material fracture model is obtained. Analysis of the obtained ratios showed that any physical action on the surface leads to a decrease in structural heterogeneity and prevents the development of cracks, increases wear resistance.

In work [5] theoretical studies on the substantiation of the methodology for modeling stationary processes of friction and wear in tribosystems under conditions of boundary lubrication are presented. The authors have developed a technique for modeling the characteristics of the actual contact spot and a mathematical model of the rate of work of dissipation in the tribosystem, which allow simulating the rate of volumetric wear and the coefficient of friction in stationary modes.

The author of the work [6] the theoretical and experimental dependences obtained using the developed model are presented and the simulation error is given, which is for the wear rate - 14,03 %, for the coefficient of friction – 12,8. The given computational models use the Q-factor of the tribosystem [7, 8].

However, the considered mathematical models do not allow determining the boundary of stable operation of the tribosystem, i.e. the boundary of the tribosystem exit to a scuffle or the boundary when accelerated wear of the materials of the triboelements begins. By analogy with the theory of automatic control, such a boundary is called the loss of stable work. Determination of such modes will improve the accuracy of modeling the processes of friction and wear in tribosystems.

Purpose

The purpose of this work is to perform the structural identification of the tribosystem and obtain a mathematical model in the form of a differential equation in the operator form, which will allow modeling the processes of friction and wear in tribosystems with the definition of the boundaries of their stable operation.

Methods

Identification of the mathematical model of the limits of functioning of tribosystems in the conditions of maximum lubrication, on a steady state without damage, is reduced to definition of the operator of tribosystem. Under the operator of the tribosystem we will understand the mathematical model of the object under study. A review of research performed on this problem suggests that the structure of the model and the type of equations that are supposed to describe the tribosystem are linear differential equations *n*-th order to the nearest coefficients.

The dynamic model of the tribosystem in the theory of identification of dynamic objects can be given in the form of an ordinary differential equation *n*-th order in the following form [9]:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} t \ldots + a_0 y(t) = b_m \frac{d^m u(t)}{dt^m} + \ldots + b_0 u(t) , \quad (1)$$

where a_i , b_j, $i = 0; 1 \ldots n$; $j = 0; 1 \ldots m$ – model parameters to be identified.

To describe a specific transition process in the tribosystem to differential equations (1) it is necessary to add the initial conditions and applying the Laplace transform, to obtain the transfer function as follows:

$$G(p)=\frac{u(p)}{y(p)}=\frac{\sum_{i=0}^{m} b_i p^i}{\sum_{i=0}^{n} a_i p^i}, \quad (2)$$

where $G(p)$ – transfer function;

p – Laplace transform parameter (differentiation operator);

$u(p)$ – input signal: load; sliding speed; the initial value of the quality factor of the tribosystem; tribological characteristics of the lubricating medium; tribosystem design;

$y(p)$ – output signal: volumetric wear rate and coefficient of friction; limits of functioning of the tribosystem.

Results

Based on the information provided above in the form of analysis of work on the development of models, as well as experimental research, which are made by the author of this work, the nature of the processes in tribosystems can be represented as the following structural and dynamic scheme, fig. 1. The structural dynamic scheme is built on the principle of two blocks connected in series.

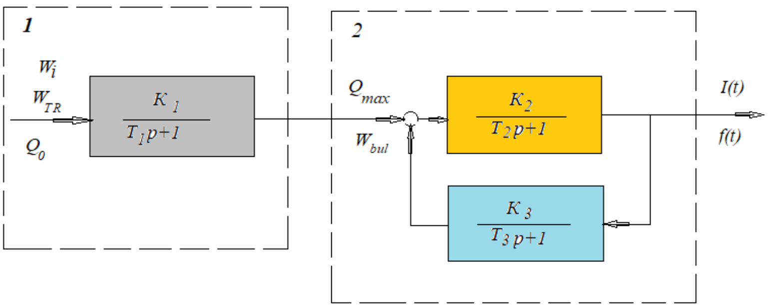

Fig. 1. Structural and dynamic scheme of modeling the functioning of tribosystems

Having considered in general the systemic model of the tribosystem, three input streams can be distinguished: matter; energy and information.

Under the input flow of matter, we mean the parameter - the quality factor of the tribosystem Q, the physical meaning of the parameter and the calculation formulas are given in the work [8]. The concept of figure of merit is defined as the ability of mating materials in a tribosystem (lubricating medium and rheological properties of the structure of materials of moving and stationary triboelements) convert the work of friction forces into thermal energy, thereby preventing energy reserves in the surface and subsurface layers of triboelements, which can be estimated by the deformable volume. The Q-factor of the tribosystem is a function of time $Q(t_i)$ and increases during the running-in time from the initial value Q_0, to the maximum possible - Q_{max}. The quality factor of the tribosystem Q determines the input flow - matter.

Under the input flow energy, we mean the parameter - the rate of work of dissipation in the tribosystem W_{TR}, which, according to work [5], is quantitatively estimated by the following expressions:

$$W_{TR} = W_{TR,m} + W_{TR,f}, \text{ [W]}. \quad (3)$$

$$W_{TR,m} = P_m \cdot n_{acs}, \text{ [W]}, \quad (4)$$

$$W_{TR,f} = P_f \cdot n_{acs}, \text{ [W]}, \quad (5)$$

where $W_{TR,m}$ and $W_{TR,f}$ – speed of dissipation in moving and fixed triboelements, J/s;

n_{acs} – number of actual contact spots (ACS) on the friction surface, determined according to work [5];

P_m, P_f – the speed of dissipation in a moving and fixed triboelement on a single actual contact spot is determined by the expressions given in the work [5]:

$$P_m = \sigma_{acs} \cdot \dot{\varepsilon}_m \cdot V_{dm}, \text{ [J/s=W]}, \quad (6)$$

$$P_f = \sigma_{acs} \cdot \dot{\varepsilon}_f \cdot V_{df} \text{ , [J/s=W]}, \tag{7}$$

where σ_{acs} – stress in the material on a unit ACS, Pa;

$\dot{\varepsilon}_m$, $\dot{\varepsilon}_f$ – material deformation rate per unit ACS, 1/s, determined by the expressions given in the work [5];

V_{dm}, V_{df} – volumes of material of a single ACS of movable and fixed triboelements, which are involved in deformation, m^3, determined by the expressions given in the work [5].

The speed of work of dissipation in the tribosystem W_{TR}, formula (3), is an energy parameter and characterizes the rate of transformation of mechanical energy into thermal energy, since the magnitude of stresses in the material σ_{acs}, volumes of materials involved in deformation V_{dm}, V_{df} and the rate of deformation in the surface layers of materials $\dot{\varepsilon}_m$, $\dot{\varepsilon}_f$ affect the "load" of triboelements in the tribosystem and depend on the load N, N and sliding speed v_{sl}, m/s. The speed of work of dissipation in the tribosystem W_{TR} defines the input flow - energy.

By the input flow - information we mean a parameter that characterizes the availability of knowledge about the stability boundary of the tribosystem, i.e. power value $W_{\max}$, at which the tribosystem begins an accelerated wear mode or a seizure occurs. The power supplied to the tribosystem is determined by the expression:

$$W_i = N \cdot v_{sl}; \left[N \cdot \frac{m}{s} = W \right], \tag{8}$$

where N – tribosystem load, N;

v_{sl} – sliding speed, m/s.

Substituting into the expression (8) maximum possible load values $N_{\max}$ or sliding speed $v_{sl(\max)}$, it is possible to determine the stability boundary of the tribosystem, i.e. the border of the tribosystem exit to scuffing or accelerated wear.

Summarizing the above direction of this work is the further development of methods for modeling stationary processes in tribosystems under boundary lubrication conditions, where the input flows will be the quality factor, the speed of the dissipation in the tribosystem, the power, which is brought to the tribosystem and the stability boundary of the tribosystem.

The target function for modeling stationary processes in tribosystems under boundary lubrication conditions will be the volumetric wear rate in the tribosystem I, m^3/hour and friction losses, which are determined by the coefficient of friction f_{fr}.

The first block, fig. 1, simulates the change in the quality factor of the tribosystem from the input value Q_0, to values $Q_{\max}$ during the running-in time. Dependences of change of rheological properties of structure of the connected materials of triboelements during running-in are resulted in works [8, 10]. From the conclusions of the robot it follows that the quality factor of the tribosystem increases and is a function of load, sliding speed, tribological characteristics of the lubricating medium and the design of the tribosystem.

Based on the analysis of works devoted to the running-in of tribosystems, we can conclude that the running-in process is an inertial link, the transfer function G_1 can be written as [9]:

$$G_1 = \frac{K_1}{T_1 p + 1}, \tag{9}$$

where K_1 – gain, which takes into account the degree of influence of the input signal (load, sliding speed, tribological characteristics of the lubricating medium), on the magnitude of the output signal (quality factor of the tribosystem), a dimensionless quantity;

T_1 – time constant of the tribosystem, which takes into account the inertial properties of the tribosystem, due to the restructuring of the structure of the materials of the surface layers during running-in, dimension s;

p – differentiation operator, used instead of the differentiation mark d/dt.

The second block of the structural and dynamic scheme, fig. 1, simulates the reaction of the tribosystem to a change in the input external action, followed by a change and stabilization of the volumetric wear rate and the friction coefficient around new values. Such processes are caused by a change in the load and sliding speed during operation, as well as a change in the tribological characteristics of the lubricating medium and the quality factor of the tribosystem. As experimental studies show, these are inertial processes.

Transmission function G_2, fig. 1, is an inertial link and characterizes the sensitivity of the tribosystem to external input influences and is determined by the expression:

$$G_2 = \frac{K_2}{T_2 p + 1}, \tag{10}$$

where K_2 – gain, which takes into account the magnitude of the change in the initial parameters (volumetric wear rate and friction coefficient) when changing the values of the input parameters (load, slip speed, quality factor of the tribosystem), the dimensionless value;

T_2 – time constant of the tribosystem, which takes into account the time during which the tribosystem returns to a steady state of operation after changing the input parameters, the dimension s;

Processes characterized by an inertial link G_2, associated with changes in the values of the roughness of the friction surfaces, the generation of heat at the spots of actual contact, the alignment of the temperature gradient in the triboelements by volume.

Transfer function G_3, which is included in the scheme of the second block in the form of negative feedback, takes into account the ability of the tribosystem to rearrange the surface layers of materials from which the triboelements are made during secondary running-in, which is connected with change of loading, sliding speed, tribological characteristics of the lubricating environment. Such processes are a function of time, which allows them to be described by an inertial link [9]:

$$G_3 = \frac{K_3}{T_3 p + 1}, \tag{11}$$

where K_3 – gain, which takes into account the degree of influence of the input signal $u(t)$ for the reconstruction of the structure of the material in the surface layers of triboelements, a dimensionless quantity;

T_3 – time constant, which takes into account the time of restructuring of the material structure in the surface layers of triboelements.

Structural and dynamic scheme, which is shown in fig. 1, reflects not the functional purpose and constructive relationship in the tribosystem, and mathematical operations that are performed when transmitting input signals (u) due to the dynamic links and properties of the tribosystem as a whole.

Applying the methods of the theory of identification of dynamic objects, it is possible to obtain an equivalent transfer function to model the functioning of the tribosystem:

$$G_{eq} = G_1 \cdot G_{eq}^{(2)}, \tag{12}$$

where $G^{(2)}_{eq}$ – equivalent transfer function of the second block according to the structural-dynamic scheme, fig. 1, which is determined by the following expression:

$$G_{eq}^{(2)} = \frac{G_2}{1 + G_2 \cdot G_3} = \frac{\dfrac{K_2}{T_2 p + 1}}{1 + \dfrac{K_2 \cdot K_3}{(T_2 p + 1) \cdot (T_3 p + 1)}}.. \tag{13}$$

After substituting formula (13) into expression (12) and converting, we obtain a total equivalent transfer function:

$$G_{eq} = \frac{(K_1 K_2 T_3) p + K_1 K_2}{(T_1 T_2 T_3) p^3 + (T_1 T_2 + T_1 T_3 + T_2 T_3) p^2 + (T_1 + T_2 + T_3) p + K_2 K_3 + 1}.. \tag{14}$$

The corresponding equation of the dynamics of the tribosystem for modeling the limits of constant modes of operation will be written as follows:

$$(T_1 T_2 T_3) p^3 + (T_1 T_2 + T_1 T_3 + T_2 T_3) p^2 + (T_1 + T_2 + T_3) p + K_2 K_3 + 1 = \\ = (K_1 K_2 T_3) p + K_1 K_2. \tag{15}$$

The third-order differential equation of the dynamics of the tribosystem functioning is written in the operator form, where the symbol p, is a differentiation operator, d/dt.

The right part of the differential equation (15) contains the first derivative of the input signal, which is represented as the product of the coefficients K_1 K_2. As shown above, the coefficient K_1 takes into account the degree of influence of the input signal (load, sliding speed, tribological characteristics of the lubricating medium), on the magnitude of the output signal (quality factor of the tribosystem), a dimensionless quantity. Coefficient K_2 takes into account the magnitude of the change of the output parameters (volumetric wear rate and friction coefficient) when changing the values of the input parameters (load, sliding speed, quality factor of the tribosystem), dimensionless quantity. The dynamics of the tribosystem is influenced not only by the value of the coefficients K_1K_2, as well as the rate of their change over time (the first derivative).

The left side of the equation is the reaction of the tribosystem to the input signal. Time constants of the tribosystem T_i have the dimension of time and characterize the inertia of the processes occurring in the tribosystem, during running-in, or during changes in operating modes.

Increasing time constants T_1 … T_3, makes the process less susceptible to changes in the input signal, the running-in process increases over time, and the tribosystem becomes insensitive to small changes in load and sliding speed. Conversely, the reduction of time constants makes the tribosystem sensitive to any external changes.

In our next works, parametric identification will be performed, the purpose of which is to determine the expressions for the calculation of the above coefficients and time constants, so that when substituting them into equation (15), the right and left parts differ the least.

Conclusions

The structural identification of the tribosystem as an object of modeling the functioning of tribosystems in the conditions of boundary lubrication is performed. It is established that the operation of tribosystems is described by a third-order differential equation and, in contrast to the known ones, takes into account the function of changing the quality factor of the tribosystem during running-in. It is shown that the nature of the functioning of tribosystems in conditions of ultimate lubrication depends on the gain and time constants included in the differential equation.

It is shown that the coefficient K_1 takes into account the degree of influence of the input signal (load, sliding speed, tribological characteristics of the lubricating medium), on the value of the output signal (quality factor of the tribosystem). Coefficient K_2 takes into account the magnitude of the change in the initial parameters (volumetric wear rate and friction coefficient) when changing the values of the input parameters (load, slip speed, quality factor of the tribosystem). Coefficient K_3 takes into account the degree of influence of the input signal on the rearrangement of the structure of the material in the surface layers of the triboelements.

The time constants of the tribosystem characterize the inertia of the processes occurring in the tribosystem, during running-in, or during changes in operating modes. Increasing the time constants makes the process less susceptible to changes in the input signal, the running-in process increases over time, and the tribosystem becomes insensitive to minor changes in load and sliding speed. Conversely, the reduction of time constants makes the tribosystem sensitive to any external changes.

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Войтов А.В. Структурна ідентифікація математичної моделі функціонування трибосистем в умовах граничного мащення.

В роботі отримав подальший розвиток методичний підхід в отриманні математичних моделей, які описують функціонування трибосистем на стаціонарних і перехідних режимах в умовах граничного мащення.

Виконано структурну ідентифікацію трибосистеми, як об'єкта моделювання функціонування трибосистем в умовах граничного мащення. Встановлено, що функціонування трибосистем описується диференційним рівнянням третього порядку та на відміну від відомих враховує функцію зміни добротності трибосистеми під час припрацювання. Показано, що характер функціонування трибосистем в умовах граничного мащення залежить від коефіцієнтів підсилення і постійних часу, які входять в диференційне рівняння.

Показано, що коефіцієнт K_1 враховує ступінь впливу вхідного сигналу (навантаження, швидкості ковзання, трибологічних характеристик змащувального середовища), на величину вихідного сигналу (добротність трибосистеми). Коефіцієнт K_2 враховує величину зміни вихідних параметрів (об'ємної швидкості зношування і коефіцієнта тертя) при зміні величин вхідних параметрів (навантаження, швидкості ковзання, добротності трибосистеми). Коефіцієнт K_3 враховує ступінь впливу вхідного сигналу на перебудову структури матеріалу в поверхневих шарах трибоелементів.

Постійні часу трибосистеми характеризують інерційність процесів, що протікають в трибосистемі, під час припрацювання, або під час зміни режимів експлуатації. Збільшення постійних часу робить процес менш сприйнятливим до зміни вхідного сигналу, процес припрацювання збільшується в часі, а трибосистема стає нечутливою до незначних змін навантаження та швидкості ковзання. І навпаки, зменшення постійних часу, робить трибосистему чутливою до будь яких зовнішніх змін.

Ключові слова: трибосистема; математична модель; диференційне рівняння; структурна ідентифікація; коефіцієнт підсилення; постійна часу; граничне мащення; добротність трибосистеми; швидкість роботи дисипації.

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Dependences of changes in the structural viscosity of oil films on the friction surface with fullerene compositions

A.G. Kravtsov

Kharkiv Petro Vasylenko National Technical University of Agriculture, Kharkiv, Ukraine
E-mail: kravcov@gmail.com

Abstract

In this work, the physical phenomenon of the formation of an oil film containing fullerenes was further developed, on the friction surface of tribosystems, which, in contrast to the known ones, takes into account the structural viscosity and structure of the formed film under the action of the electrostatic field of the friction surface. An increase in load significantly increases the structural viscosity of the gel structure, 13 - 20 times. The concentration of fullerenes in the base lubricant does not significantly affect the dynamic viscosity of aggregates in the composition of the liquid and the structure of the gel.

An increase in the tribological properties of the base lubricant medium reduces the value of the structural viscosity of the gel on the friction surface by a factor of 3. At the same time, the concentration of fullerenes in the range of 0.5 - 1.5% does not have a large effect on these indicators. This phenomenon can be explained by the presence or absence of an additive package in the base lubricating medium. For those oils where the additive package is absent or present in a small amount $E_{spec} = (1{,}8...3{,}6)\cdot 10^{14}$ J/m^3, the introduction of a fullerene composition promotes the formation of clusters and micelles, which increase the structural viscosity and, consequently, form a film on the friction surface in the form of a gel structure. Conversely, if fullerenes are introduced into a base oil that contains a large and balanced additive package, where tribological properties are high $E_{spec} \rangle (3{,}6 - 7{,}2)\cdot 10^{14}$ J/m^3, interaction at the molecular level does not occur. Fullerenes to a lesser extent will form stable aggregates in the form of micelles.

The effect of reducing the coefficient of friction, equal to 96 %, is typical for low and medium loads of operation of tribosystems and base lubricants with average values of tribological properties. With increasing loads or tribological properties of base oils, the effect of the use of fullerenes decreases.

Keywords: fullerenes, oil film, fullerene compositions, structural viscosity, sol structure, gel structure, electrostatic field of the friction surface, dynamic viscosity.

Introduction

The use of fullerenes as anti-wear, extreme pressure and antifriction additives to technical liquid lubricants gives an ambiguous answer about their effectiveness. There is a direction where fullerenes, in the form of nanopowders, are directly introduced into the lubricant and the direction, where pre-dispersion of fullerenes is used in solvents, for example, vegetable high oleic oils, and then the introduction of such compositions into technical oils. According to the authors of the work [1], this use of fullerenes gives a better positive effect than the addition of fullerenes in the form of nanopowders to lubricants.

The general structural feature of liquid lubricants in the presence of fullerenes in them is that clusters and micelles are formed in the volume of the liquid. Based on the findings [2] it can be argued that a viscous liquid can be considered as a continuous dispersion medium, and clusters and micelles as a dispersion phase. Fullerene molecules interacting with each other and oleic acid molecules of vegetable oil form aggregates, and the viscous liquid medium becomes structured.

Literature review

Author of the work [3] claims that structured fluids form aggregates in the form of doublets or chains, chains can form a continuous grid. The interaction of aggregates in the volume of fluid is expressed in the formation of sufficiently strong compounds, primarily of coagulation origin. Anisometric units are able to rotate when the layers of liquid are shifted. According to the author of the work [3] rheological properties of suspensions due to the volume concentration of the dispersed phase, the magnitude of the forces of interaction between aggregates and particles and the structure of the formed aggregates. The author considers Brownian motion of particles to be the main factors influencing the process of aggregate formation, gravitational and repulsive forces that occur between particles, hydrodynamic interaction between particles.

In our opinion, when considering the processes of friction and wear, when the friction surfaces accumulate electrostatic charge [1], it is necessary to consider the forces of electrostatic interaction between the units of the dispersed phase and the friction surface. It should be borne in mind that the concentration of units in the field of electrostatic forces of the friction surface will be greater than at a distance from the surface where the field does not act.

According to the conclusions of the work [2] units of the dispersed phase, combined by external electrostatic forces into a continuous grid (frame) on the friction surface, acquire the properties of a "solid".

Insignificant external load forms elastic deformation of a skeleton. At high enough loads, the frame collapses and the individual units disconnect. In this case, according to the authors [2], individual units (clusters and micelles of fullerenes) can form a rotational motion between the friction surfaces. When such an interaction mechanism occurs, the viscosity of the fluid gradually decreases [2].

The above conclusion is accepted by us as a working hypothesis of reduction of friction forces in tribosestopics in the presence of a dispersed phase in the lubricant, which will be further confirmed by theoretical models and experimentally.

The presence in the volume of the lubricant of the dispersed phase in the form of clusters and micelles requires, along with the total dynamic viscosity of the liquid, to consider the "structural viscosity". This concept was introduced in the work [4]. The use of the concept of "structural viscosity" allows to take into account not only the dynamic viscosity of the liquid, but also the dynamic viscosity of the units that are in the volume of the liquid, taking into account the shear rate.

The authors of the work [5] provides an overview of the literature on lubricants with added nanoparticles. The effect of nanoparticles on the tribotechnical characteristics of oils is analyzed. It is noted in the work that the use of nanoadditives to lubricants leads to an increase in the viscosity of the base medium, high bearing capacity of the interface, reducing the coefficient of friction, increasing wear resistance.

In work [6] theoretical studies of changes in the structural viscosity of oil films on the friction surface with fullerene compositions in the field of action of electrostatic forces of the friction surface and the base lubricant are presented. Based on the working hypothesis, it was theoretically established that for a thin oil film located in the field of action of electrostatic forces of the friction surface, the structural dynamic viscosity of the lubricant must be considered, which at the friction surface has gel structures, and as the electrostatic forces from the friction surface decrease, the gel structure transforms into a sol structure.

It is shown that the value of the structural viscosity of the considered aggregates is comparable with the viscosity of polymers or bitumen. In this case, the viscosity of the gel structure is four orders of magnitude higher than the viscosity of the sol structure. An increase in the concentration of fullerenes leads to an increase in the dynamic viscosity of aggregates.

It has been shown theoretically that the structure of the oil film, which corresponds to the structure of the gel, belongs to the class of non-Newtonian liquids. With an increase in the slip rate, the dynamic viscosity of such structures decreases by a factor of 4, which is explained by the destruction of micelle clusters and the appearance of rotational motions of elastic flocks. It is assumed that this will lead to a decrease in the value of the coefficient of friction. It is shown that for the gel structure, the concentration of fullerenes in the bulk of the base lubricant does not have a large effect on the structural viscosity. Conversely, for the structure of a sol, the concentration of fullerenes has a significant effect on the value of the structural dynamic viscosity.

Purpose

The aim of this work is to obtain theoretical dependences of the effect on the structural viscosity of oil films containing fullerene compositions in the field of action of electrostatic forces of the friction surface, operating factors, such as load, tribological properties of the base lubricant.

Methods

In developing a microreological model for the formation of a thin film of lubricant on the friction surface under the action of electrostatic forces, the following assumptions were made.

1. The dispersion of clusters and micelles in the volume of liquid lubricant outside the action of the electrostatic field of the friction surface is taken as the structure of the sol [4]. In this structure, stresses are perceived by a viscous liquid medium and transmitted to elastic units. This structure has viscoelastic properties.

2. The dispersion of clusters and micelles near the friction surface (in the field of electrostatic forces), take the structure of the gel [6], where between the micelles and the friction surface there are forces of electrostatic interaction, which contribute to the formation of a framework of units, the cavities between which are filled with a viscous fluid. This structure has elastic and viscous properties. Intermicellar forces can relax, respectively, the structure behaves like Maxwell's body [4]. In such a structure, stresses are perceived by the elastic elements of the units and transmitted to a viscous liquid medium.

3. A tribosystem was chosen for modeling: a movable triboelement steel 40H (HRC52); fixed triboelement Br.AZh 9-4 (HB 100); friction area of the movable triboelement $F_{fr\,m} = 0{,}0003$ m^2, fixed $F_{fr\,f} = 0{,}00015$ m^2; ring-to-ring interface. The sliding speed was constant and amounted to v_{sl} = 0,5 m/s; load varied within N = 600…1800 N; the tribological properties of the lubricating medium varied within $E_{spec} = (1{,}8...7{,}2)\cdot 10^{14}$ J/m^3.

Results

Based on the expressions that are given in the work [6], the structural viscosity of the sol μ_s and gel μ_g can be determined:

$$\mu_s = k_l\mu_l + k_f\mu_K,\ \text{Pa·s}, \tag{1}$$

$$\mu_g = k_l\mu_l + k_f\mu_M,\ \text{Pa·s}, \tag{2}$$

where μ_s and μ_g – structural dynamic viscosity of sol and gel, which are formed under the action of the electrostatic force field of friction surfaces, dimension Pa·s;

k_l, k_f – dimensionless coefficients that take into account the mass concentration of fullerenes per unit of lubricant outside the field of action of electrostatic forces and on the friction surface, in the field of action of electrostatic forces;

μ_l – dynamic viscosity of the base lubricant, dimension Pa·s;

μ_K, μ_M – dynamic viscosity of aggregates of structures consisting of Kelvin bodies and Maxwell bodies, dimension Pa·s [7].

Calculation formulas for determining the above parameters are presented in the work [6].

Dependences of changes in the structural dynamic viscosity of a thin oil film on the friction surface, in the field of action of electrostatic forces, which consists of aggregates of Maxwell's bodies μ_M and gel structures μ_g, are shown in fig. 1 and fig. 2.

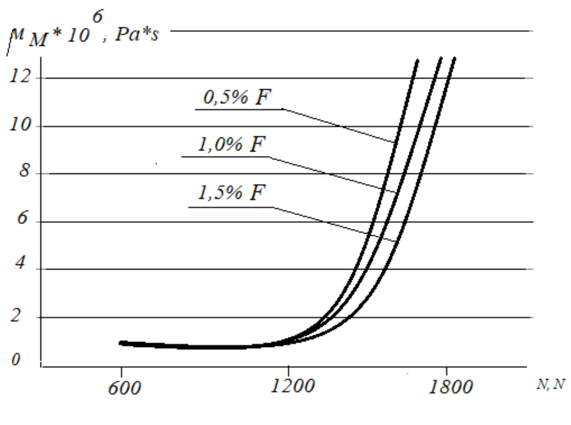

Fig. 1. Dependences of changes in the structural viscosity of aggregates consisting of Maxwell's bodies on the load and concentration of fullerenes

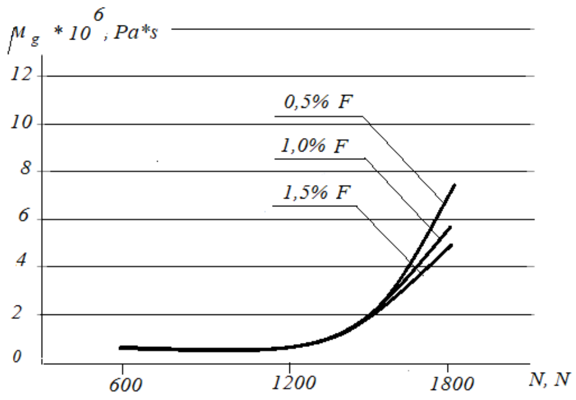

Fig. 2. Dependences of the change in the dynamic viscosity of the gel structure on the load and the concentration of fullerenes

The nature of the change in the presented dependencies allows us to draw the following conclusions.

As follows from the presented dependences in fig. 1 and fig. 2 an increase in load significantly increases the structural viscosity of aggregates in the form of a Maxwell body, fig. 1 and the viscosity of the gel structure, 13 - 20 times, fig. 2. The concentration of fullerenes in the base lubricant does not significantly affect the dynamic viscosity of aggregates in the composition of the liquid and the structure of the gel. Such an increase in the dynamic viscosity of the gel structure can be explained by the squeezing out of a viscous liquid under load and, thereby, a decrease in its content in the gel structure.

The general conclusion for the presented dependences is that with an increase in the load, the structure of the oil film on the friction surface in the presence of fullerene compositions acquires the properties of an "elastic solid". In this case, the concentration of fullerenes in the basic lubricating medium does not play a large role.

Modeling the nature of the change in the structural viscosity in the field of action of electrostatic forces of the friction surface with a change in the tribological properties of the base lubricant medium and the concentration of fullerenes in this medium is shown in fig. 3 and 4.

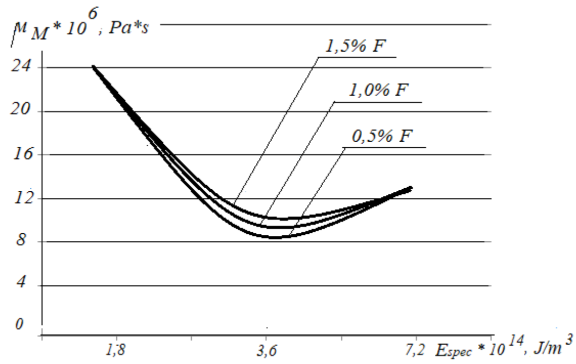

Fig. 3. Dependences of changes in the structural viscosity of aggregates consisting of Maxwell bodies on the tribological properties of the lubricating medium and the concentration of fullerenes

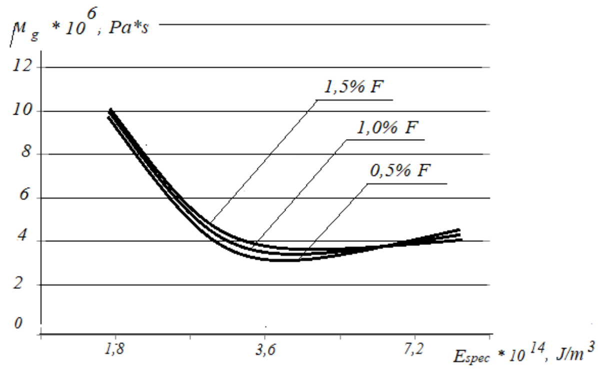

Fig. 4. Dependences of the change in the dynamic viscosity of the gel structure on the tribological properties of the lubricating medium and the concentration of fullerenes

The following lubricating media were used in the modeling: hydraulic oil MGP-10, $E_{spec} = 1{,}8 \cdot 10^{14}$ J/m^3; motor oil M-10G$_2$k, $E_{spec} = 3{,}6 \cdot 10^{14}$ J/m^3; transmission oil VALVOLINE GL-5, $E_{spec} = 7{,}2 \cdot 10^{14}$ J/m^3. Determination of the tribological properties of lubricating media as a parameter E_{spec} - specific work of wear, presented in the work [8].

As follows from the presented dependences, an increase in the tribological properties of the lubricating medium reduces the value of the structural viscosity of aggregates in the form of Maxwell bodies, fig. 3 and the structural viscosity of the gel on the friction surface by a factor of 3, fig. 4. At the same time, the concentration of fullerenes in the range of 0.5 - 1.5% does not have a large effect on these indicators. In our opinion, this phenomenon can be explained by the presence or absence of an additive package in the base lubricating medium. For those oils where the additive package is absent or present in an insignificant amount $E_{spec} = (1{,}8...3{,}6) \cdot 10^{14}$ J/m^3, the introduction of a fullerene composition promotes the formation of clusters and micelles, which increase the structural viscosity, and consequently, form a film on the friction surface in the form of a gel structure. Conversely, if fullerenes are introduced into a base oil that contains a large and balanced additive package, where tribological properties are high $E_{spec} \rangle (3{,}6 - 7{,}2) \cdot 10^{14}$ J/m^3, interaction at the molecular level does not occur. Fullerenes to a lesser extent will form stable aggregates in the form of micelles.

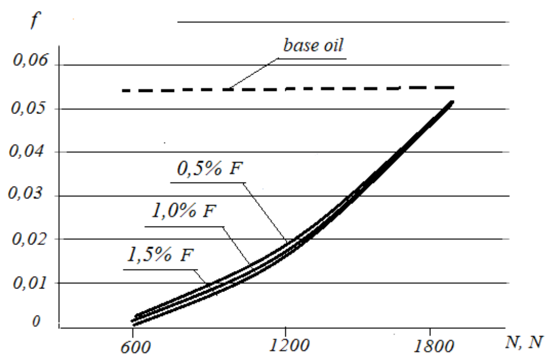

Fig. 5. Dependences of the change in the friction coefficient of the tribosystem on the load and the concentration of fullerenes

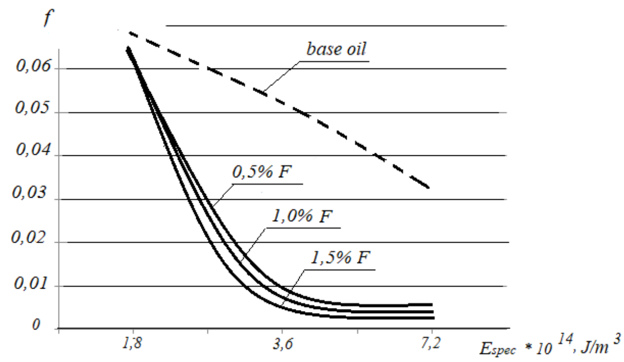

Fig. 6. Dependences of the change in the friction coefficient of the tribosystem on the tribological properties of the lubricating medium and the concentration of fullerenes

The change in the structural dynamic viscosity of a thin oil film on the friction surface made it possible to theoretically obtain the dependence of the change in the friction coefficient on the change in the load on the tribosystem and the concentration of fullerenes in the base oil, which is shown in fig. 5. The dashed line shows the change in the friction coefficient when the tribosystem operates on base oil, M-10G$_2$k, solid lines in the presence of different concentrations of fullerenes in the base oil.

Analysis of the presented dependences allows us to conclude that the maximum effect when using fullerenes is observed at low and medium loads. The effect of reducing the coefficient of friction at $N = 600$ N equal to 96 %, at $N = 1200$ N – 66 %. At maximum load N = 1800 N, the effect is 7,2 %. At the same time, a change in the concentration of fullerenes in the range from 0.5 % to 1.5 % affects the change in the coefficient of friction in the range of 3 – 5 %.

Theoretically, the dependences of the change in the friction coefficient on the tribological properties of the base lubricating medium were obtained E_{spec} and the concentration of fullerenes in this medium, which are shown in fig. 6. The dashed curve corresponds to the change in the friction coefficient of the tribosystem on base oils without the use of fullerenes, solid lines for oils with different concentrations of fullerenes.

Analysis of the presented dependences allows us to assert that the introduction of fullerenes into hydraulic oils with low values of tribological properties $E_{spec} = 1{,}8 \cdot 10^{14}$ J/m^3 reduces the coefficient of friction by 4 %. The maximum effect of reducing the coefficient of friction, equal to 83 – 98 %, is typical for oils with $E_{spec} = 3{,}6 \cdot 10^{14}$ J/m^3. These are mid-quality oils, which include engine oil M-10G_2k.

The use of base oils with $E_{spec} \rangle 3{,}6 \cdot 10^{14}$ J/m^3 does not lead to an increase in the effect of reducing the friction coefficient from the use of fullerenes, the friction coefficient remains constant. In this case, the magnitude of the change in the coefficient of friction when using different concentrations of fullerenes is within 13 %.

Based on the above theoretical studies, it is possible to form a general conclusion on the use of fullerenes in lubricants of various qualities. The maximum effect of reducing the friction coefficient, equal to 83 – 98 %, can be obtained with oils of an average level of tribological properties.

Conclusions

The physical phenomenon of the formation of an oil film containing fullerenes on the friction surface of tribosystems was further developed, which, in contrast to the known ones, takes into account the structural viscosity and structure of the formed film under the action of the electrostatic field of the friction surface. An increase in load significantly increases the structural viscosity of the gel structure, 13 - 20 times. Such an increase in the dynamic viscosity of the gel structure can be explained by the squeezing out of a viscous liquid under load and, thereby, a decrease in its content in the gel structure. The concentration of fullerenes in the base lubricant does not significantly affect the value of the dynamic viscosity of the aggregates in the composition of the liquid and the structure of the gel.

An increase in the tribological properties of the base lubricant medium reduces the value of the structural viscosity of the gel on the friction surface by a factor of 3. At the same time, the concentration of fullerenes in the range of 0.5 - 1.5% does not have a large effect on these indicators. This phenomenon can be explained by the presence or absence of an additive package in the base lubricating medium. For those oils where the additive package is absent or present in an insignificant amount $E_{spec} = (1{,}8...3{,}6) \cdot 10^{14}$ J/m^3, the introduction of a fullerene composition promotes the formation of clusters and micelles, which increase the structural viscosity and, consequently, form a film on the friction surface in the form of a gel structure. Conversely, if fullerenes are introduced into a base oil that contains a large and balanced additive package, where tribological properties are high $E_{spec} \rangle (3{,}6 - 7{,}2) \cdot 10^{14}$ J/m^3, interaction at the molecular level does not occur. Fullerenes to a lesser extent will form stable aggregates in the form of micelles.

The effect of reducing the coefficient of friction, equal to 96 %, is typical for low and medium loads of operation of tribosystems and base lubricants with average values of tribological properties. With increasing loads or tribological properties of base oils, the effect of the use of fullerenes decreases.

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Кравцов А.Г. Залежності зміни структурної в'язкості мастильних плівок на поверхні тертя з фулереновими композиціями/

Дістало подальший розвиток фізичне явище формування масляної плівки з фулереновими композиціями на поверхні тертя трибосистем, яке, на відміну від відомих, враховує структурну в'язкість і структуру сформованої плівки під дією електростатичного поля поверхні тертя. Збільшення навантаження значно збільшує структурну в'язкість структури гелю, в 13 - 20 разів. Таке підвищення динамічної в'язкості структури гелю можна пояснити видавлюванням в'язкої рідини під навантаженням і тим самим, зменшення її змісту в структурі гелю. Концентрація фулеренів в базовому змащувальному матеріалі не робить істотного впливу на величину динамічного в'язкості агрегатів в складі рідини і структури гелю.

Збільшення трибологічних властивостей базового мастильного середовища знижує величину структурної в'язкості гелю на поверхні тертя в 3 рази. При цьому концентрація фулеренів в межах 0,5 - 1,5% не робить великого впливу на дані показники. Дане явище можна пояснити наявністю або відсутністю пакета присадок в базовому мастильному середовищі. У тих олив, де пакет присадок відсутній або присутній в незначній кількості $E_y = (1{,}8...3{,}6)\cdot 10^{14}$ Дж/м^3, введення фулеренової композиції сприяє утворенню кластерів і мицелл, які збільшують структурну в'язкість, а отже і утворюють на поверхні тертя плівку у вигляді структури гелю. І навпаки, якщо вводити фулерени в базову оливу, яка містить великий і збалансований пакет присадок, де трибологічні властивості високі $E_y \rangle (3{,}6-7{,}2)\cdot 10^{14}$ Дж/м^3, взаємодія на молекулярному рівні не відбувається. Фулерени в меншій мірі будуть утворювати стійкі агрегати у вигляді міцел.

Ефект зниження коефіцієнта тертя, що дорівнює 96%, характерний для малих і середніх навантажень експлуатації трибосистем і базових мастильних матеріалів із середніми значеннями трибологічних властивостей. При збільшенні навантажень або трибологічних властивостей базових олив, ефект від застосування фулеренів зменшується.

Ключові слова: фулерени; мастильна плівка; фулеренові композиції; структурна в'язкість; структура золю; структура гелю; електростатичне поле поверхні тертя; динамічна в'язкість

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Durability of working bodies of soil-cultivating machines strengthened by composite electrolytic coatings (CEC)

M.S. Stechyshyn[1], A.O. Kornienko[2], N.M. Stechyshyna[1], A.V. Martynyuk[1*], M.I. Tsepeniuk[3], V.O. Herasymenko[4]

[1]Khmelnitsky National University
[2]National Aviation University
[3]Therpolsky National Technical University named after. I. Pulyuya
[4]Sumy National Agrarian University
E-mail: [*]avmart@khmnu.edu.ua

Abstract

The task of this work is to find the optimal ratio between the size of the particles of silicon carbide and their volumetric content in the nickel matrix to provide maximum characteristics of strength and wear resistance of the working bodies of soil-processing machines.

The article investigates the processes of forming complex electrolytic coatings (CEC) on a nickel basis with particles of the filler of various sizes of silicon carbide (SIC). It has been established that the formation of a sicle size sicle and SiC_5 is carried out on a vertical, and all other particles in a horizontal cathode. The volumetric content of SIC_{nano} and SiC_5 particles in nickel reaches a maximum of about 10%, and SiC_{100} – 46 %.

Cap with particle size 28/20 and 50/40 μm allow you to get the most wear-resistant coatings. In this case, the coating with particles 28/20 μm have higher wear resistance, but coating with particles 50/40 μm are more technological when they are formed.

The size of the filler particles has a significant effect on the tribological characteristics of the CEP, namely wear resistance and friction coefficient. It has been established that the highest wear resistance and the smallest friction coefficients are characterized by coatings having as a filler of fractions 28/20 and 50/40 μm. Tribological studies show the promise and efficiency of the CEP to increase the wear resistance of the working bodies of soil-cultivating machines.

Key words: ground-making machines, composite electrolytic coatings (CEC), durability.

Introduction and relevance of the problem

Physical and mechanical characteristics of the CEC based on a nickel matrix containing a silicon carbide (SIC) are largely determined not only by the geometric dimensions of SIC particles, but also their volumetric content in the nickel matrix. Thus, in [1] it is indicated that there is a proportional dependence between the hardness of particles, their number in a nickel matrix and durability. The maximum strength value is achieved with the optimal content of particles in the coating, the excess of which dramatically reduces the physical and mechanical characteristics of the CEC. Therefore, the task of this work is to find the optimal ratio between the size of the particles of silicon carbide and their volumetric content in the nickel matrix to provide maximum characteristics of strength and wear resistance of the working bodies of soil-processing machines.

Analysis of recent researches

The problem of increasing the wear resistance of the working bodies of soil-cultivating machines is devoted to a significant number of scientific works [1...4].

Numerical studies indicate the existence of various approaches to solve this problem. Thus, in the paper [1], the issues of strengthening the blades of soil-processing operations of agricultural machines are considered to form the effect of self-combustion, and in [2] distinguish structural, operational and technological methods for increasing the wear resistance of working bodies of soil-cultivating machines. Technological methods include primarily selection of materials and heat treatment, which provide high wear resistance in conditions of abrasive wear [1 - 4].

In [3], it has been shown that the use according to optimal modes of carbaazonation in a non-hydrogen teaching discharge allowed to increase the wear resistance of the cultivator's paws in 1.7...1.8 times.

The author of work [4], the following materials for the manufacture of parts operating in the abrasive mass are recommended: manganese steel (30Г, 50Г, 65Г, 110Г6Х3Л), steel doped chromium (38ХА, 40Х, 45Х, Х12, Х12Ф1, Х6ВФ), multicomponent doped steel and alloys (12ХН3А, 17ХГ2СФР, 08Х18Н10Т), solid sintered alloys (ВК6, ВК8, ВК15, ВК20).

Technical requirements for discs to domestic technology provides for their manufacture of steel 65Г, or its substitute - steel M76 and steel 45 with heat treatment on hardness 39...44 HRC. Disks of foreign manufacturers are made of more durable steels, in particular the discs of the Bellota firms - from the steel 28MnB5, CASE Firms - from Earth Metal. The cost of such disks in 2.0 ... 2.3 times higher than the cost of domestic disks and has 20 ... 30% higher wear resistance [2]. The use of high-quality metals and alloys are economically inappropriate, so the output should be searched in the used methods of surface strengthening of working surfaces.

Surface reinforcement is used to increase wear resistance in cases where there are no increased requirements for the volume strength of parts, but their high surface durability is required.

In agricultural machinery, 90% of all strengthening works are induction surfacing. The main disadvantage of this method is the high cost of alloys for surfacing [2].

Laps of cultivators are one of the most mass details of the working bodies of agricultural machines. As a result of small service life, a large number of pieces are spent in the form of spare parts, the production of which requires a significant amount of high-quality metal.

In accordance with the technical requirements, the guarantee experience of the archery legs of the cultivator should be no less than 25 hectares, but as shows the practice of exploiting such working bodies, their work for refusal on various soils does not exceed 14 - 19 hectares.

At present, in Ukraine, serial working bodies of soil-cultivating machines are made of steels 65Г, 45 and Л53, which in a tempered state (hardness 37 ... 43HRC) have satisfactory indicators of relative elongation but a small boundary of strength (σ_v = 880...1080 μPa). According to many years of research and analysis of the results of operating tests of ro-cultivating machines, only for the first year of operation due to breakage (or deformation with subsequent breakage), about 40% of ploughshare and 15% shelves, 20% of cultivators and 30% of different types of disk working bodies [1].

Studies [5] shows that application for strengthening laser heat treatment allows 1.3 ... 1.4 times reduce the wear of parts of cutting elements in comparison with bulk quenching, and the use of laser surfacing of the Alloy ПС - 14-60 + 6% B4C in 1.7 ... 1.8 times compared to the basic induction surfacing technology. Laser technologies provide local heating in the absence or minimum deformations with the next cooling of strengthened products. Receiving high physical and mechanical properties of surface layers is associated with a high heating and cooling rate, which is 104-106 ºC/s.

In general, it can be stated that for most regions of Ukraine, one set of details of the working bodies of soil-cultivating machines is not enough on the current annual cycle (spring + autumn), and therefore it is necessary to continue the searches for new, economically substantiated methods and methods of surface strengthening of the working bodies of soil-cultivating machines.

Thus, the purpose of the study is to develop a technology for strengthening the working bodies of soil-cultivating machines by applying composite electrolytic coatings (CEC).

Materials, electrolytes and electrolysis modes when forming a heart

In the scientific literature, the prospects of use of nickel as a matrix for the next formation of a heap of different composition, filling and properties are noted. Nickel is characterized by high affinity to most types of filler particles. Nickel Based CEC is divided into several types: core, multilayer coatings with increased corrosion resistance in the atmosphere, self-residual coatings, etc.

The analysis of cermetes conducted in [6] indicates a great curiosity of researchers to this type of coatings. In this case, their high thermal resistance and good mechanical properties are noted. Thus, the Ni-SiC coating can operate at a temperature of 2600 ºC. A similar coating with a thickness of 200 is firmly coupled with steel and retains hardness (HRC 63) to 260. The coil layer 25 on steel is deformed without hacking with a special steel ball. With multiple immersions of Ni-SiC coated products in water after its heating up to 650 cracks are not formed. The Ni-SiC is used instead of a chromium coating and service life while increases several times [6].

It is also noted [7, 8] that the cathode extraction of the current and the productivity of the coating process is quite high, and the electrolytes for deposition of nickel are simple and reliable.

Choosing a filler for a chest is determined by the requirements for the properties of the coating: high strength of grip with matrix, affinity with matrix material, corrosion resistance in aggressive environments, highly high mechanical characteristics, etc.

Such requirements will some extent satisfy the powders of carbides and, in particular, silicon carbide. The silicon carbide is recommended for the creation of compositions to increase the hardness and wear resistance in friction without lubrication and at elevated temperatures [6, 7, 8], corrosion resistance [7]. The silicon carbide in the nickel matrix improves the coating properties: microhardness increases by 1 ... 2.5, internal stresses decreases in 3 ... 8 times, and corrosion resistance increases in 4 ... 50 times [8]. Coverage with silicon carbide has the best grip with steel compared to other fillers. By strength of grip with the base we have such a row: 487-SiC; 213-TiC; 216-Cr7C3 [6].

In addition, silicon carbide has high mechanical characteristics: microhardness 29 ... 35, elastic modulus E=394, border strength to the rupture -180, to bend -173 ... 225, on compression -800 [8].

The silicon carbide has a low cost and is produced in large quantities in the form of powders packed by fractions.

Based on the above, in the work are a nickel base with a filler of sic different fractions from 100/80 to nanoparticles of less than 50. Thus, the SiC powders with dimensions are used in the work: less than 50 - nanoparticles; M5; 28/20; 50/40; 100/80. According to SiC particles in the future, the following designations are given: $Ni\text{-}SiC_{nano}$; $Ni\text{-}SiC_5$; $Ni\text{-}SiC_{28}$; $Ni\text{-}SiC_{50}$; $Ni\text{-}SiC_{100}$.

For the formation of a cavity on a nickel matrix, sulfate or sulfatchloricular nickel electrolytes [6, 7] is used for the most part. The disadvantage of such electrolytes is a low rate of precipitation of nickel: 20...40 with a current density of 0.2...0,5. Increasing current density leads to a deterioration of the quality of the coating.

In this paper, a chloride nickel electrolyte was used, which allows to increase the cathode density of current, increase the rate of depositing nickel [9]. The composition of the electrolyte is given in Table.1.

Table 1

Composition and characteristics of a nickel of electrolyte chloride [6, 7]

Composition of electrolyte, g/l	Technological modes of electrolysis
$NiCl_2 \times 6H_2O$ - 300 H_3BO_3 - 40. Sodium lauryl sulfate - 0.01 ... 0.02	Acidity of pH 3...4. Operating temperature t = 60 ... 70 ºC. Catholic density of current I_c = 1 ... 3 kA/m^2. Nickel precipitation rate υ_0 = 90 ... 100 μm/h

To the advantages of the selected nickel electrolyte include the stability of the value of pH throughout the time of electrolysis, which eliminates the effects of acidity change on the volume content of the filler particles into a cavity.

The electrolyte was additionally administered to sodium pair lauryl sulfate in an amount of 0.01 ... 0.02, which according to [8] contributes to the inclusion of SiC particles in the coating and improves the conditions for increasing the nickel matrix.

Also, the amorphous boron powders were added to the size of the amorphous boron in size about 1, which is due to the possibility of interaction of boron and nickel with the subsequent heat treatment of coating and obtaining new structures (solid solutions, eutectics, dispersion-solid alloys).

The SiC and B powders were injected directly before the formation of a cavity in an amount from 10 to 110, depending on the location of the cathode, electrolysis modes, and the required volumetric content of the filler particles in the nickel matrix.

Samples for applying the CEC were made of steel 40X. CEC was applied to the working and side surface of the sample. The choice of the sample form is due to the need to conduct in further tests on the cavitation-erosion wear resistance of the obtained coatings for MSV. The same samples were used for electrochemical measurements and potentiostatic studies.

Operational, including tribological and especially cavitation-erosionary characteristics of wear resistance of the CEC depend on the strength of the coupling (adhesion) of the coating with the base. The force of adhesion clutch with a steading base (steel 40X) depends on the degree of surface cleaning from oxides and other chemical compounds. Therefore, before applying CEC, samples are degreased by Viennese lime and subjected to anode treatment for 3... in a 20% solution of sulfuric acid with a density of current 2.

The general view of the installation for the anodic cleaning of the samples is shown its principal electrical circuit in Fig. 1.

As an anode, nickel plates were used for the formation of the specimens 65 × 35 ×5 mm.

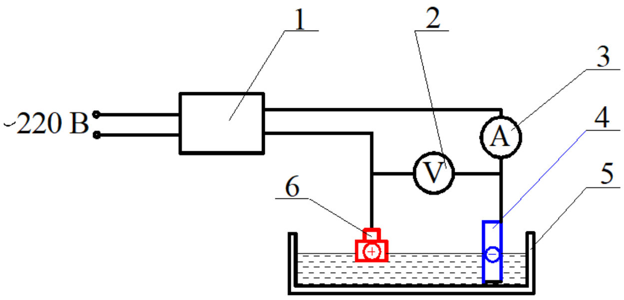


Fig. 1. Principlable electrical scheme of installation for anodic cleaning of samples before applying CEC:
1 – block of DC power;
2 – voltmeter;
3 – ammeter;
4 – nickel plate;
5 – bath;
6 – sample

The coatings with the inclusion of SiC particles larger than 10 were formed on a horizontal cathode in a pulse mixing mode, and with a particle size of up to 10 on a vertical cathode with a continuous mixing with a magnetic stirrer, for example, a cavity with the inclusion of amorphous boron and particles SiC size 50 and M5 ($SiCi_{nano}$ and SiC_5).

The current density determines the rate of precipitation of the matrix metal. For selected nickel-chloride electrolyte (Table 1), the permissible current density reaches 3, and working-2.0 [7]. According to the results of studies [8], the coatings were carried out with a current density in the range of 0.4 ... 1.0.

To increase the mechanical characteristics of the resulting CEC, their annealed at temperatures above 200. According to [8] at a temperature of 200 and exposure to 1 ... 2 in the Ni-B system are formed by the nickel borid.

The temperature of the formation of eutectics in the Ni-B system is 1060 ... 1080 [8], and therefore annealing in a vacuum in an ОКБ 8086 was performed at a temperature of 1100, kept 3...5 and cooled together with the furnace.

Formation of the Ni-SiC_{nano} and Ni-SiC5 cavity, as well as with the inclusion of amorphous boron, was carried out on a vertical cathode with a continuous stirring of a suspension on the installation developed by us [10]. Formation of cells with particles SiC_{28}, SiC_{50}, SiC_{100} with the addition of amorphous boron powders was carried out on a horizontal cathode. Changing the content of particles in the matrix was regulated by a change in relation and (mixing / sedimentation time) and a change in the concentration of SiC particles and in in the electrolyte.

The number of particles of boron and silicon in the coating was determined by methods of chemical and metallographic analyzes.

The volumetric content of the filler particles depends on the geometric particle sizes. The maiden-shaped users contained as much as 8 % vol. for SiC_{nano} and up to13% by volume for SiC_5.

Testing for friction and wear

To study the antifriction properties of the composite coatings, the car of M22-M (Fig. 2) was used, which allows in the process of conducting an experiment to automatically record the main characteristics of friction and wear (linear wear of steam and friction coefficient) without removing the sample from the car. As a result, rollers were used in diameter 40 mm, made of tempered steel 45 (HRC 45-48). At a distance of 0.5 mm from the surface of friction, a chromel-digestive thermopore was injected, which allows you to control the temperature change in the friction zone and judge the stabilization of friction and wear processes. Testing samples with coatings were carried out under friction without mammary according to the scheme of the shaft-plane (Fig. 3), loading with rubbed formed P = 20; 40; 60; 150 N, speed of sliding v = 0.5 m/s. The rubbing path L = 1 km.

The frictional knot M22-M (Fig.2) consists of a housing 3, in which moving bearings is mounted shaft 11. At the end of the shaft fixing movable contracement 4. On the housing 3 mobile on bearings mounted carriage 2, the axis of which coincides with the axis. Rotation of the shaft 11. Caret 2 is fixed by rotation of the carriage 12, interacting with the dynamometer spring 1. The deformation of the dynamometer spring 1 is controlled by the linear displacement sensor 13, fixed on the rack 14. On the carriage of the carriage 10 in the guide 6 installed assembly 7 with the ability to radial displeasure Regarding the axis of the hall 11. A plant 7 is fixed in a fixed sample 5, which are in conjunction with a mobile countertop 4. In the hole of a caliper 7 is freely located in a radial direction of rod 8, one end of which freely rests into the rear side of the sample 5 and the second in the sensor of linear movement 9, fixed on the bracket 10. Rod 8 is made of material with a small coefficient of thermal expanded.

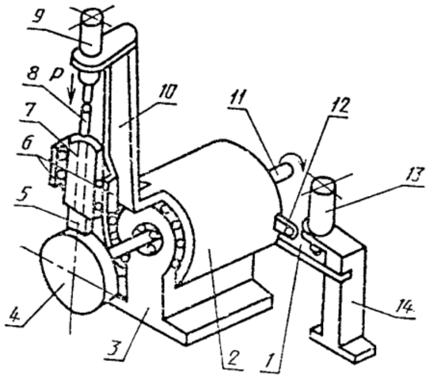


Fig. 2. Scheme of friction node

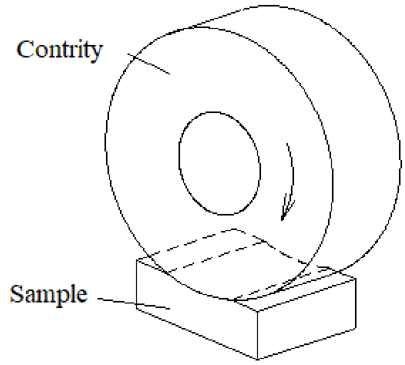


Fig. 3. Scheme friction shaft-plane

The size of the samples on which 10 × 10 × 5 mm test were performed (Fig. 3, Fig. 4). Before testing the sample and the countertoll was washed with gasoline, acetone and alcohol and dried in air. Determined the mass of the sample and counterparted with an error of not more than 0.0005g. With the help of lab scales (the largest limit of weighing 200g, weighing error is not more than 0,0005g). In the test process, friction coefficient and linear frictional wear are recorded during sustainable wear. The end of the work was determined by stabilization of temperature and friction coefficient. Recording coefficient of friction and linear wear of frictional steam during test was performed every 5 minutes. The intensity of wearing samples with coatings was evaluated by loss of mass of the sample and the magnitude of linear friction pair [8].

After each test, the counterattack and sample were removed from the machine, washed with gasoline, acetone and alcohol and dried in air. Determined the mass of the sample and counterbalanced with an error of not more than 0.0005g by means of laboratory scales.

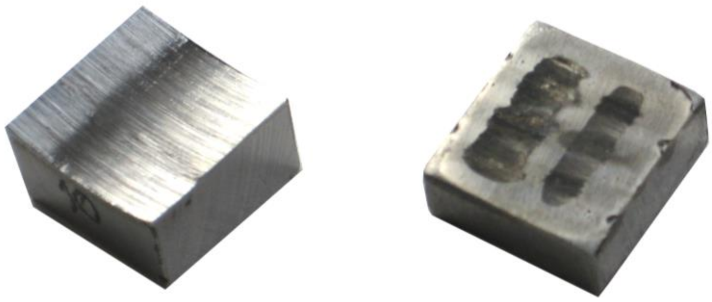


Fig. 4. Samples from a CEC after friction test

The intensity of the wear of the sample and counterticked and (mg/km) was determined by the formula:

$$I = (m_1 - m_2)/L,$$

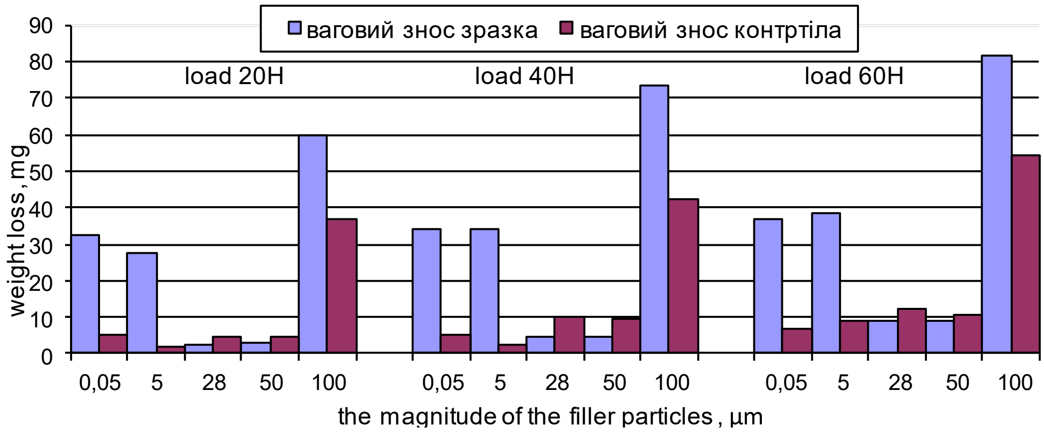
where: m_1 – mass of sample (countertick) to test, mg;
m_2 – mass of sample (countertick) after testing, mg;
L – rubbing path, km.

Research results

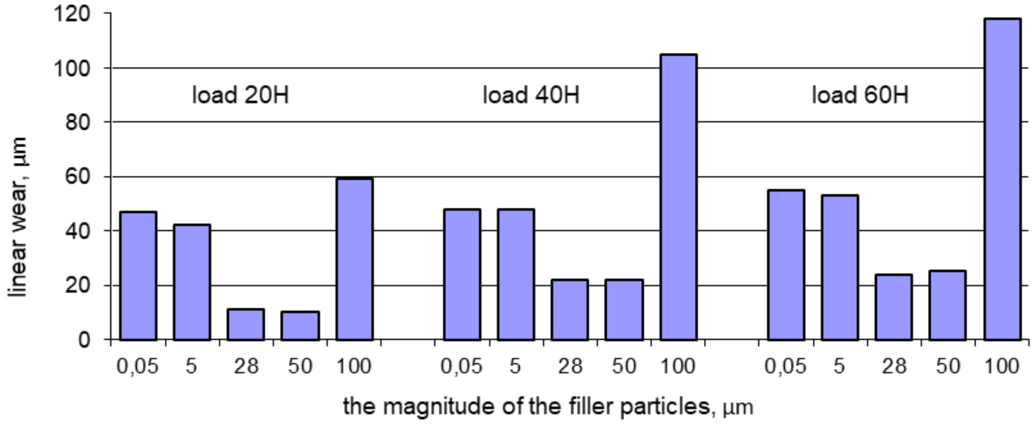
Physical and mechanical characteristics of the CEC based on a nickel matrix containing a silicon carbide (SiC) are largely determined not only by the geometric dimensions of SiC particles, but also their volumetric content in the nickel matrix. Thus, in [7], it is indicated that there is a proportional dependence between the hardness of particles, their number in a nickel matrix and durability. The maximum strength value is achieved with the optimal content of particles in the coating, the excess of which dramatically reduces the physical and mechanical characteristics of the CEC.

Thus, the coating on a nickel base with particles of sic different fractions and for convenience, we will denote coating by the size of the filler particles. For example, nickel bp with particles SiC fractions 5/10 µm, denote both $Ni + SiC_5$, fractions 28/20 µm as $Ni + SiC_{28}$, 50/40 µM - $Ni + SiC_{50}$, 100/80 - $Ni + SiC_{100}$, and coating with nanoparticles in size about 50 nm - $Ni + SiC_{nano}$. When conducting work also used amorphous boron dispersion of about 1 µm.

Studies have shown that the size of the filler particles has a significant impact on the wear resistance of the coating. According to the results of experiments, the largest linear wear with loads of 20 and 40 N have specimens from steel 40X without coating. When applied to a steel layer of galvanic nickel, which has a hardness Hμ = 2.4 ... 2.7 GPa, linear friction pair decreases by 1.4 times, weight demolition of the sample - by 2 times, and countertil in 3 ... 7.6 times Compared to test samples without coating (Fig. 5).



a



b

Fig. 5. Wearing resistance of Ni-SiC CEC, depending on the size of the filler:
a – weight wear of the sample and countertick, mg / km;
b – linear friction pair of friction, μm / km

Wearing resistance of samples from the CEC containing the SiC filler of different fractions is higher than in purely nickel coatings. So, for samples with the inclusion of a fraction of 100/80 μm there is a significant weight and linear wear, which even exceeds the wear of the sample without coating. The hardness of the matrix with this slightly increased and is Hμ = 2,8 - 3,0 GPa, that is, increased by 10 – 15 % compared with a clean nickel due to composite strengthening and larger stresses in the matrix. The obtained results are explained by the fact that the size of the particles is compared with the coating thickness (200 - 300μm) and in these conditions, the plastic nickel matrix can not compensate for contact loads on large SiC particles, which leads to fragile destruction and distorting. In addition, the volumetric content of SiC_{100} particles in the coating is the largest compared to other test samples and is 46 %. Under such a carbide content, significant stresses that the plastic matrix can not be compensated effectively.

A large weight wear of the sample is observed in the application as a filler for small particles of fraction less than 5 μm and nanoparticles 50 nm (Fig. 5). The use of such particles slightly increases the wear resistance of the coating in comparison with galvanic nickel, but not significantly (a decrease in weight loss of the sample is 10 – 20 %) because the content of SiC_5 particles and SiC_{nano} was 8 and 3 vol % respectively, that is, it is less than large particles and such particles are more efficiently strengthening the matrix (disperse hardening occurs) than increasing wear resistance in comparison with larger particles. This is due to the fact that in such compositions, the particle size is smaller than the size of individual contact spots, they can not effectively perceive the load and therefore the main contribution to wear resistance introduces the NI matrix, which has low mechanical properties and due to the emergence of significant stresses possible occurrence of cracks [8] .

The highest wear resistance among the above coatings have a cap with the inclusion of fractions 28/20 and 50/40 μm that have the smallest wear with all loads. The content of the filler in such coatings is, respectively, 24 and 28 vol%. In this case, slightly less wear is covered with the inclusion of a fraction of 28/20 μm. Weight wear of such samples is an order of magnitude smaller than for coatings with smaller and large particles. Compared to galvanic nickel, such coatings have a decrease in wear 12, 9 and 5 times with loads of 20, 40, 60 N, respectively (Fig. 5).

The highest wear resistance of coatings with inclusion of 28...50 μm may be due to the distribution of load they perceive. The solid inclusion load is equal to the actual contact pressure when their sizes are smaller or vessel with a single contact spot (2 - 10 μm). For compositions with optimal particle sizes (28 μm) there are no processes of seizing, abrasive and fragile destruction and there is a normal mechano-oxidation process of wear.

In addition to wear resistance, an important tribotechnical parameter is the coefficient of friction f. An analysis of the test results showed that the coefficient of friction significantly affects the load when the SiC filler and the size of the SiC filler and clearly follows such a regularity that with an increase in loading such as friction decreases (Fig. 6). This is due to the fact that with an increase in normal load n, the friction force FTR increases not so significantly and, accordingly, the ratio $f = F_{tr} / N$ decreases.

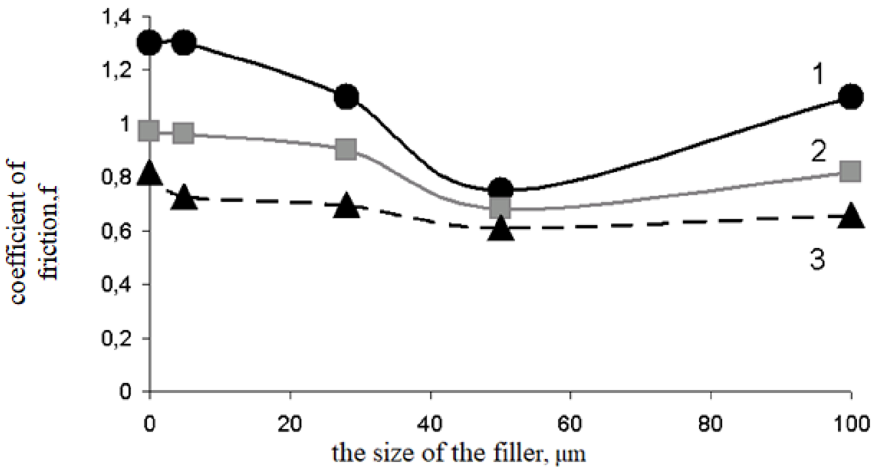


Fig. 6. Dependence of coefficient of friction f from the size of the particles of the filler CEC:
1 – load 20 n;
2 – 40 N and 3 - 60 N

As to the influence of the size of the particles of the filler of the CEC on the friction coefficient F, it can be noted that the friction coefficient decreases and for the range of particles of filler 40 ... 60 μm friction coefficient is minimal. For coatings with larger filler particles (fraction 100/80) friction coefficient is greater. This can be explained by the fact that for small particles of the contact spot is greater than the size of the particles and friction occurs on a nickel matrix that has a high friction coefficient and is prone to gripping. For particles of larger than 10 μm, the size of the contact is smaller than the size of the particles and the main contribution to the friction is introduced by the filler particles, which contributes to the reduction of friction coefficient and increased wear resistance. For large particles it is possible to distort them and the abrasive destruction begins. It can also be noted that for greater loads (60N), the effect of the size of the filler particles on the friction coefficient decreases, while there is a greater difference between the friction coefficients of nickel coatings (F = 0.82) and filling coes (F = 0.73 and below). . Probably, with larger loads of solid particles, the filler begins to perceive more efficiently load, which in turn positively affects the friction processes.

Practical recommendations

1.Formation of a sac with particles SiC_{nano} and SiC_5 is carried out on a vertical, and all other particles in a horizontal cathode. With such particles, we obtain the highest corrosion resistance of the coating.

2.The volumetric content of particles SiC_{nano} and SiC_5 in nickel reaches a maximum of about 10 %, and SiC_{100} – 46 %.

3.Cap with particle size 28/20 and 50/40 μm allow you to get the most wear-resistant coatings. In this case, the coating with particles 28/20 μm have higher wear resistance, but coating with particles 50/40 μm are more technological when they are formed.

Conclusions

1.Sumulary of filler particles has a significant effect on the tribological characteristics of the CEC, namely wear resistance and friction coefficient. It has been established that the highest wear resistance and the smallest friction coefficients are characterized by coatings having as a filler of fractions 28/20 and 50/40 μm.

2.Tribological studies show the promise and efficiency of the use of a cavity to increase the wear resistance of the working bodies of soil-cultivating machines.

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Стечишин М.С., Корнієнко А. О., Стечишина Н.М., Мартинюк А.В., Цепенюк М.І., Герасименко В. О. Зносостійкість робочих органів ґрунтообробних машин зміцнених нанесенням КЕП

У статті досліджено процеси формування комплексних електролітичних покриттів (КЕП) на нікелевій основі з частинками наповнювача різних розмірів карбідом кремнію (SiC). Встановлено,що формування КЕП з розмірами $SiC_{нано}$ і SiC_5 проводиться на вертикальному, а усіх інших за розміром частинок на горизонтальному катоді. Об’ємний вміст частинок $SiC_{нано}$ і SiC_5 в нікелі сягає максимуму в середньому біля 10%, а SiC_{100} – 46%.

КЕП з розмірами частинок 28/20 та 50/40 мкм дозволяють отримати найбільш зносостійкі покриття. При цьому покриття з частинками 28/20 мкм мають вищу зносостійкість, але покриття з частинками 50/40 мкм є більш технологічними при їх формуванні.

Розмір частинок наповнювача має значний вплив на трибологічні характеристики КЕП, а саме зносостійкість та коефіцієнт тертя. Встановлено, що найвищою зносостійкістю та найменшими коефіцієнтами тертя характеризуються покриття, що мають у якості наповнювача порошки фракцій 28/20 та 50/40 мкм. Трибологічні дослідження показують перспективність і ефективність застосування КЕП для підвищення зносостійкості робочих органів ґрунтообробних машин.

Ключові слова: ґрунтообробні машини, зносостійкість, формування комплексних електролітичних покриттів

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Website: http://tribology.khnu.km.ua/index.php/ProbTrib
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Technological factors influence on the antifriction coatings quality

I.V. Shepelenko

Central Ukrainian National Technical University, Ukraine
E-mail: kntucpfzk@gmail.com

Abstract

The conditions for the antifriction coatings formation during finishing antifriction non-abrasive treatment (FANT) are analyzed. The requirements for this kind of coatings and the main criteria for assessing their quality are noted. A relationship has been established between the quality of the coating obtained with FANT and the technological factors that determine the conditions for contacting the tool with the treated surface. It is proved that the shape and size of microroughnesses of the treated surface determine the efficiency of the microcutting process and filling the microcavities with the rubbed material.

Technological factors influence on the coating quality was investigated during FANT by implementing a multifactor experiment, as a result of which a connection was established between the technological parameters of the process (total friction path, load on the tool), as well as the length of the supporting surface with indicators characterizing the coating quality.

Statistical models were obtained for mass transfer of antifriction material, area (continuity) of the coating and surface roughness at natural values of the factors, which made it possible to establish the studied factors influence on the optimization parameters.

The analysis of the experimental scattering graphs made it possible to clarify the nature of the factors changes and analyze their mutual influence on the optimization criteria. Taking into account the inversely proportional relationship of the optimization criteria, the achievement of their maximum values at the same time is impossible, therefore, the values are taken according to the final result of the FANT process.

The range of the studied factors values is established, the regularities of their change are substantiated from the point of view of the selected optimization criteria. Determination the rational values of the FANT process technological parameters will improve the antifriction coatings quality obtained by a friction-mechanical method.

Key words: finishing antifriction non-abrasive treatment (FANT), antifriction coating, optimization, continuity coating, mass transfer, roughness.

Introduction

A generally recognized direction in the field of the working surfaces of machine parts quality improving is the development and widespread use of antifriction coatings [1]. From all the variety of methods for obtaining antifriction coatings, coatings with optimal values of hardness and elasticity modulus with increased antifriction properties, providing the favorable internal stresses creation, as well as maximum adhesion characteristics of the coating with the base material, seem to be preferable [2].

Such kind of coatings can be obtained by frictional rubbing of plastic metals by finishing antifriction non-abrasive treatment (FANT) [3]. Rubbing the friction surface with a tool made of copper and its alloys in the presence of a process fluid makes it possible to create coatings with a thickness of 2 - 5 microns on the friction surface, as well as to harden the surface of the base material to a depth of 70-80 microns due to high pressure at the point of linear contact. FANT, characterized by environmental friendliness, makes it possible to reduce the running-in time of parts, eliminate scuffing of friction surfaces, increase the bearing capacity of parts and joints, protect the friction surface from hydrogen wear, reduce the friction temperature and extend the operating period of the friction unit when the lubricant supply is turned off, reduce the coefficient of friction, etc. [4].

The antifriction coating formation during FANT largely depends on technological factors that determine the conditions for contacting the tool with the treated surface, and the shape and size of microroughnesses determine the quality of the resulting coating, its continuity [5]. The study of the contacting surfaces features, as well as the main parameters of the FANT process, their regularities will improve the antifriction coating quality, and hence the operational properties of the part. In this regard, studies of the main parameters influence of the FANT process on the formation of an antifriction coating, depending on the conditions of contact interaction of a copper-containing tool with a treated surface, seem to be very relevant.

The widespread use of FANT is also hindered by the lack of extensive information on the relationship between the technological factors of the process and the geometric parameters of the surface layer, and above all, with the roughness, which, according to a number of researchers [6, 7], is one of the main criteria for the resulting coating quality. Thus, it becomes necessary to conduct special studies of the technological factors influence that determine FANT on the antifriction coating quality.

Literature review

A number of requirements are imposed on antifriction coatings, regardless of the methods of their formation, the main of which should be attributed [8]:

- density and continuity;
- high adhesion to the metal surface;
- uniformity of the coating in thickness and a sufficiently high cleanliness of its surface;
- the ability, together with the base metal, to withstand operational loads;
- durability.

These requirements determine the coatings quality obtained with FANT.

In a number of studies devoted to the formation of the FANT antifriction coating, the authors of studies [9] consider surface roughness to be one of the main criteria for assessing the quality of the applied skin. Earlier it was proved that the surface roughness parameters are one of the main factors that determine the intensity of the friction pairs wear [10], in a certain way affect the indicators of its physical state (cold-hardening, internal stresses, microcracks, structure) [11] have a significant effect of roughness on corrosion resistance [12] and on the reliability of parts fixed joints [13]. Due to the fact that the authors of [14] obtained and substantiated the initial microrelief of the surface to create favorable conditions for microcutting the antifriction material with microprotrusions of the initial surface and to improve the coating formation quality by the friction-mechanical method, it becomes necessary to conduct special studies of the FANT influence with the established parameters on the roughness of surface layer.

According to [7], such parameters as the coating thickness, as well as its adhesion to the base material, play a key role in the coatings quality. An important factor is the stress-deformed state of the surface layer and the initial microgeometry.

In [15], as an assessment of the coatings quality obtained with FANT, the following were used: the coating thickness, the degree of its porosity, the roughness parameter, and wear resistance. It should be noted the inconsistency of information available in the available literature. Thus, the authors of [16] obtained a coating thickness by the friction method in the range of 0.3 - 0.5 microns, and in [17], a coating thickness of about 30 - 40 microns was obtained. Such a large difference in the results indicates the need for additional studies to determine the coating thickness.

The authors of [18] made an attempt to optimize the process of applying antifriction coatings. For this purpose, the quality of processing was assessed using points, and the parameters were taken: the color of the coating; reducing the length of the rubbing rod - the intensity of rubbing; uneven coating - gaps in the applied layer; smoothing the coating layer. This approach to assessing the coating quality and the effectiveness of the FANT technology, according to [15], is inaccurate, since the color, thickness, porosity and other indicators are indirect characteristics of the coating quality, they can be used at the stage of testing the coating technology. The main indicator of the coating quality is its wear resistance (ability to resist wear).

The results of wear tests of antifriction coatings formed by the friction-mechanical method from various materials (brass, bronze, copper) are presented in [19]. However, the difference in coating applying modes, the lack of information about measuring instruments raise doubts about the information reliability and the experimental technique correctness.

The given data of literary sources do not allow assessing the effectiveness of the FANT technology. In this regard, it becomes necessary to conduct research to determine the influence of the technological parameters of the FANT process on the coating quality obtained by the friction-mechanical method.

Purpose

The aim of the work is to establish the basic laws of the technological factors influence of the FANT process on the resulting coating quality.

Research Methodology

To achieve this goal, the greatest difficulty is presented by studies to determine the factors influence on the optimization parameters. Such studies should include the influence on the indicators characterizing the applied coating quality (area (continuity), roughness and mass transfer of antifriction material from the tool) of the main processing modes: the friction path L and the load on the tool P, as well as the supporting surface length of the treated sample Δl. In order to reduce the number of experiments for these studies, the planning of experiments was carried out.

The study of the surface, processed by the FANT friction-mechanical method, was carried out on special samples of gray cast iron SCH20 made in the form of disks, on which a preliminary applied microrelief with different Δl (Fig. 1).

a **b** **c**

Fig. 1. Samples of cast iron SCH20,
processed by the FANT friction-mechanical method with different Δl:
a – Δl = 0,2 mm;
b – Δl = 0,4 mm;
c – Δl = 0,6 mm

The friction path was changed within 2 ... 30 mm by varying the length of the brass tool (Fig. 2) and the number of its passes.

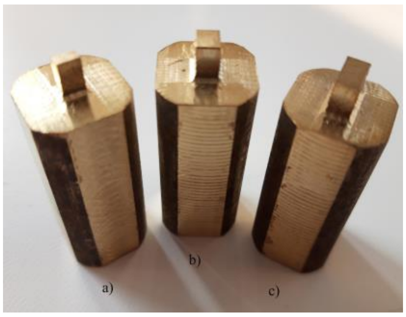


Fig. 2. Tools for frictional mechanical processing with different lengths l:
a – l = 2 mm;
b – l = 4 mm;
c – l = 6 mm

Thus, the total friction path was calculated taking into account the tool size using the formula:

$$L = l \cdot N \,, \tag{1}$$

where – l is the length of the tool, mm;

N – is the number of cycles (passes) of the tool.

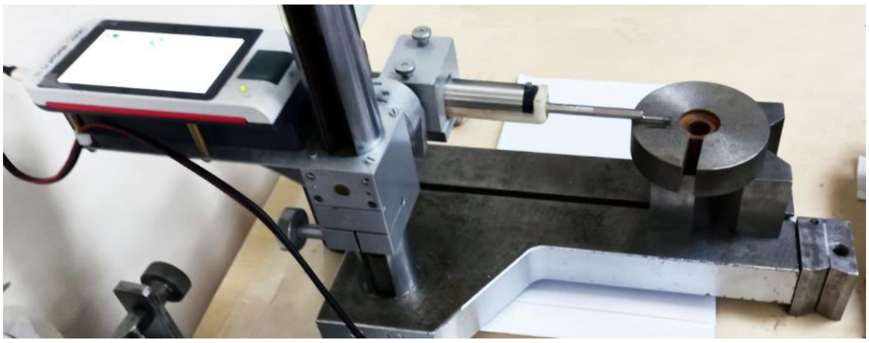
The value of mass transfer was determined by weighing the instrument before and after FANT on a TBE-0,21-0,001 laboratory scales (Fig. 3, a) according to the formula:

$$\Delta m = m_1 - m_2 \,, \tag{2}$$

where – m_1 is the tool mass before FANT, g;

m_2 – tool mass after FANT, g.

a



b

**Fig. 3. Weighing a brass tool after FANT (a)
and measuring the roughness of the machined surface (b)**

Under the selected conditions and processing modes, antifriction coatings were applied on the surface of the studied samples (Fig. 4) by a friction-mechanical method using a setup developed by the authors [20].

**Fig. 4. Studied samples with an antifriction coating applied
by a friction-mechanical method**

Coverage area (continuity) based on the results of metallographic analysis of the surface using digital image processing methods on a PC. For this purpose, a program was written in C ++ using the Qt framework and the OpenCV image processing libraries.

Surface roughness before and after FANT was assessed using a Mahr XR20 profilograph (Fig. 3, b), a PC-based device that allows to determine more than 75 parameters of roughness, waviness, P-profile and Motif-parameters in accordance with international standards.

The aim of the experiments series was to implement a matrix of the central compositional plan 2^3 + star points, resulting in the factors influence ($L \times n$ (total friction path), P_{Σ} (force per 1 microroughness of 1 mm of its width), Δl (length contact)) on the indicators characterizing the coating quality obtained with FANT.

Results

The STATISTICA 12.0 application software package was used to process the experimental data, as a result of which statistical mathematical models were constructed for the coating mass m (Y_1), the coverage area S_n/S (Y_2) and the surface roughness $R_a/R_{a\ init}$ (Y_3) at natural values of factors:

$$Y_1(m) = 0,005519 + 0,000735 \cdot x_1 - 0,000462 \cdot x_2 - 0,001442 \cdot x_3 - \\ -0,001895 \cdot x_1^2 - 0,001603 \cdot x_2^2 - 0,001799 \cdot x_3^2 + \\ +0,000248 \cdot x_1 \cdot x_2 + 0,000306 \cdot x_1 \cdot x_3 - 0,00031 \cdot x_2 \cdot x_3. ; \quad (3)$$

$$Y_2\left(S_n/S\right) = 0,668755 + 0,044408 \cdot x_1 - 0,056635 \cdot x_2 - 0,275208 \cdot x_3 - \\ -0,199841 \cdot x_1^2 - 0,200608 \cdot x_2^2 - 0,149047 \cdot x_3^2 - \\ -0,014875 \cdot x_1 \cdot x_2 - 0,042875 \cdot x_1 \cdot x_3 + 0,006198 \cdot x_2 \cdot x_3. ; \quad (4)$$

$$Y_3\left(R_a/R_{a\ ucx}\right) = 0,626308 - 0,088358 \cdot x_1 - 0,00778 \cdot x_2 + 0,077667 \cdot x_3 + \\ +0,163163 \cdot x_1^2 + 0,048406 \cdot x_2^2 + 0,061634 \cdot x_3^2 - \\ -0,017354 \cdot x_1 \cdot x_2 + 0,015312 \cdot x_1 \cdot x_3 + 0,003099 \cdot x_2 \cdot x_3, . \quad (5)$$

where x_1 – is the total friction path, mm;

x_2 – force per 1 microroughness of 1 mm of its width, N;

x_3 – contact length, mm.

As an example, a standardized Pareto map for the surface roughness $R_a/R_{a\ init}$ is shown in Fig. 5.

After analyzing the Pareto map for surface roughness (Fig. 5), we note the maximum influence on the optimization criterion Y_3 parameters x_1 (total friction path), x_3 (contact length) and x_2 (force per 1 microroughness of 1 mm of its width), which determine the change in surface roughness. Response surfaces and graphs of equal output lines for $R_a/R_{a\ init}$ are shown in Fig. 6. Their analysis allows us to note that the lowest surface roughness is achieved with the following values of factors:

$x_1 \to L \times n$ = 18…20…22 mm; $x_2 \to P_\Sigma$ = 110…130…150 N; $x_3 \to \Delta l$ = 0,3…0,35…0,4 mm.

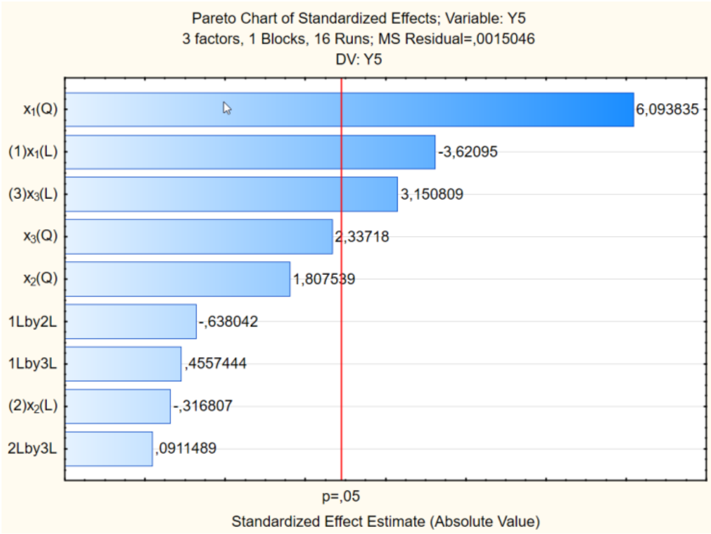


Fig. 5. Standardized Pareto map for surface roughness $R_a/R_{a\ init}$

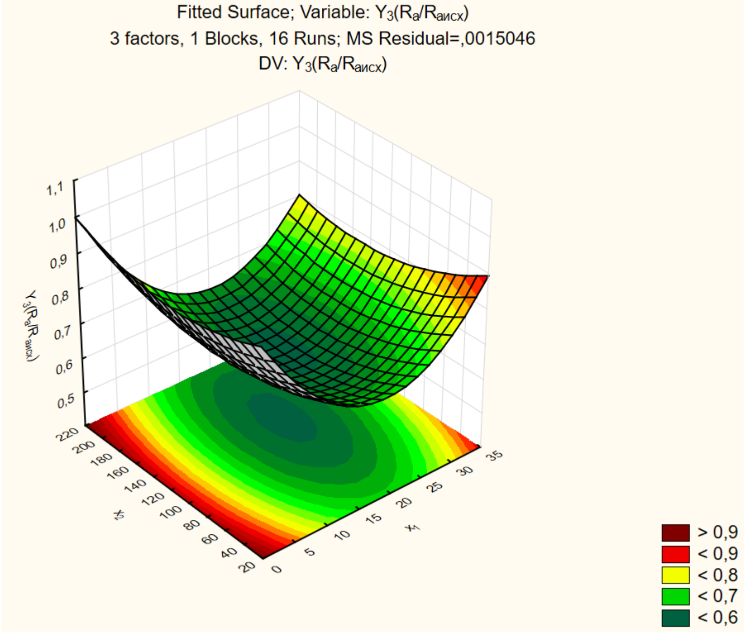


Fig. 6. Response surfaces and graphs of equal output lines (Y_3) $R_a/R_{a\ init}$

Similar calculations were performed for other parameters $Y_1(m)$, $Y_2(S_n/S)$.

Given the inversely proportional relationship of the optimization criteria $Y_1(m)$ and $Y_2(S_n/S)$ with $Y_3(R_a/R_{a\ init})$, achieving their maximum values is impossible at the same time, which shows the difference in the rational values of some parameters, especially parameters x_3 and x_1, therefore take the required value of this parameter based on the final result of the FANT process.

Analysis of experimental scattering graphs makes it possible to clarify the nature of factors changes and analyze their mutual influence on the three optimization criteria. Thus, when increasing the friction path $x_1(\Delta L)$ to 18 … 20 mm, the maximum effect of mass transfer of antifriction material is achieved. Further growth of the friction path does not increase it. This is due to the fact that the most active transfer is on the first passes of the tool. Increasing their number does not significantly affect the subsequent results of the process. In turn, the increase in the force per 1 microroughness of 1 mm of its width $x_2(P)$ to the value of 100 … 140 N also contributes to the growth of mass transfer. However, a further increase of this technological parameter reduces the transfer of antifriction material. This nature is associated with the deformation process of the cast iron surface layer, and the increase in effort contributes to the strengthening of graphite inclusions. Cast iron becomes denser, ie there is a strengthening of cast iron. Note that the increase in mass transfer occurs at the value of the contact length $x_3(\Delta l)$ = 0.3…0.5 mm.

Since the mass transfer of antifriction material and the area of the coating has a direct relationship, it should be noted such a pattern. At values of $x_1(\Delta L)$ = 18 … 20 mm; $x_2(P)$ = 100 … 140 N; $x_3(\Delta l)$ = 0.2…0.3 mm, the largest coverage area is observed, which is explained by the considerations described above.

The lowest surface roughness occurs at the values of the friction path $x_1(\Delta L)$ = 18 … 22 mm. Subsequent rubbing cycles do not increase the antifriction coating quality. With an increase in the force per 1 microroughness of 1 mm of its width $x_2(P)$ to values of 110 … 150 N, there is a decrease in surface roughness, due to intense mashing of antifriction material (brass L63) in the depressions of microprotrusions and smoothing of their vertices. The most rational values of the contact length $x_3(\Delta l)$ in terms of reducing the treated surface roughness occurs at values of 0.3 … 0.4 mm. This once again proves the influence of the surface microrelief size on the coating quality obtained with FANT.

Conclusions

Analyzing the response surfaces and graphs of equal output lines for optimization criteria and scattering graphs of technological factors, we can conclude that the rational friction path is 12 mm, which is sufficient to achieve quality coverage from the standpoint of the considered criteria. Regarding the force per 1 microroughness of 1 mm, it can be stated that its rational value for increasing the mass transfer of antifriction material, the coating area and reducing the surface roughness is the value at 105 N. Regarding the value of the support surface to be treated, it should be noted that its rational value within 0.4 mm is clearly traced for all optimization criteria. Determined technological parameters of the FANT process will improve the quality of antifriction coatings obtained by friction-mechanical method.

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Шепеленко І.В. Вплив технологічних факторів на якість антифрикційних покриттів.

Проаналізовано умови формування антифрикційних покриттів при фінішній антифрикційній безабразивній обробці (ФАБО). Окреслено вимоги до подібного роду покриття тномера основні критерії, які застосовуються під час оцінювання їх якості. Зазначено взаємозв'язок між якістю покриття, отриманого при ФАБО, і технологічними чинниками, що визначають умови контактування інструмента з оброблюваною поверхнею. Доведено, що форма і розміри мікронерівностей оброблюваної поверхні визначають ефективність протікання процесу мікрорізання і заповнення мікрозападин антифрикційним матеріалом.

Дослідження впливу технологічних чинників на якість покриття при ФАБО виконувалося шляхом реалізації багатофакторного експерименту, в результаті якого встановлено вплив технологічних параметрів процесу (сумарний шлях тертя, навантаження на інструмент), а також довжини опорної поверхні на показники, що характеризують якість покриття. Отримано статистичні моделі для масоперенесення антифрикційного матеріалу, площі покриття (суцільність) і шорсткості поверхні при натуральних значеннях чинників, що дало змогу встановити вплив досліджуваних факторів на параметри оптимізації.

Аналіз експериментальних графіків розсіювання дав підстави уточнити характер змін чинників і проаналізувати їх взаємний вплив на критерії оптимізації. Враховуючи зворотно-пропорційний зв'язок критеріїв оптимізації, досягнення їх максимальних значень одночасно неможливе без врахування кінцевого результату процесу ФАБО. Встановлено діапазон значень досліджуваних чинників, обґрунтовано закономірності їх зміни у фокусі вибраних критеріїв оптимізації. Визначення раціональних значень технологічних параметрів процесу ФАБО дасть змогу підвищити якість антифрикційних покриттів, отриманих фрикційно-механічним способом.

Ключові слова: фінішна антифрикційна безабразивна обробка (ФАБО), антифрикційне покриття, оптимізація, суцільність покриття, масоперенесення, шорсткість.

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E-mail: tribosenator@gmail.com

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Influence of basalt fiber on tribological properties of secondary polyethylene terephthalate

A.-M.V. Tomina*, A.V. Yeromenko, V.S. Makarov

Dniprovsk State Technical University, Ukraine
**E-mail: an.mtomina@gmail.com*

Abstract

The article considers the influence of discrete (3 mm) basalt fiber on the tribological properties of secondary agglomerated polyethylene terephthalate. It was found that the introduction of the filler reduces the coefficient of friction and the intensity of linear wear of the initial polymer 1,5 and 4,5 times, respectively, reaching the minimum values at a basalt fiber content of 5 mass.%. The obtained results are due to the fact that the appearance of basalt fiber strengthens the polymer matrix that confirms the increase in hardness by 15%, and inhibits the development of cracks on the surface of the composite. The study of the temperature in the contact zone showed its increase that is due to the low thermal conductivity of the filler (0,064 - 0,096); as a result, there is an accumulation of heat in the friction zone. Further increase in fiber content (up to 10 mass.%) leads to a sharp deterioration of the tribological and physico-mechanical properties of basaltoplastics because of the increase in the defect of the material. It is determined that the effective content of filler in the polymer matrix is 5 mass.%. As a result, this composite was recommended for the manufacture of parts for movable joints of agricultural, automotive and metallurgical equipment.

Key words: polyethylene terephthalate, basalt fiber, coefficient of friction, intensity of linear wear, temperature in the contact zone, hardness, roughness.

Introduction

Nowadays the ecological situation in Ukraine and around the world is very close to critical. Thus, as of 2019, the volume of municipal solid waste (MSW) of polymers amounted to 215 million tons. 20 % of them were sent for recycling, and only 10 % were actually recycled. At the same time, 4,8 - 12,7 million tons fall into the ocean [1].

Widespread methods of the disposal of municipal solid waste, including polyethylene terephthalate (PET), are incineration, recycling, pyrolysis, decomposition and reusing. However, these methods are characterized by a number of such disadvantages as: environmental (release of toxic substances has a negative impact on the human body and the environment) and economic (periodic or semi-continuous principle of operation).

Actually, one of the common practices of the disposal of municipal solid waste is the creation of composite materials (CM) of structural (lattice drainage systems, covers and housings of hatches, bottoms of bodies and door modules of cars), general (waterproof furniture, park benches [2, 3]) and tribotechnical (gears, sliding bearings) purpose. Secondary use of MSW allows obtaining a number of such advantages as: improvement of the ecological situation, due to safe utilization of PET waste and increase of economic efficiency (the cost of secondary PET is 40 % lower than the primary) [4].

Therefore, the search for new effective contains of CM, including tribotechnical purposes, on the basis of secondary waste is an urgent task for scientists.

Literature review

In the XXI[st] century much attention is paid to the possibility of recycling different polymeric materials, including polyethylene terephthalate. Recycling can reduce the negative impact on the environment and return valuable polymer raw materials to the production process.

The performance characteristics of secondary PET differ slightly from the ones of primary PET. But they have low toughness index and wear resistance. To improve the technical properties of polyethylene terephthalate, various modifiers are introduced. They are: bifunctional organic compounds, dispersed (polycarbonate, quartz glass, crushed gravel, slag, sand, fly ash) and fibrous (basalt wool, fiberglass) fillers.

Today basalt fibers (BF) are one of the promising fillers for the creation of CM. The use of BF will allow to obtain CM with a high indicator of wear resistance, low coefficient of thermal linear expansion, resistance to moisture, acids and alkalis. These composites can be successfully used instead of serial materials (cast iron, steel and non-ferrous alloys) in the manufacture of parts of tribological joints in the automotive, agricultural and metallurgical industries [5-7].

Given the above, the aim of the work was to study the influence of discrete basalt fiber on wear, coefficient of friction and hardness of secondary agglomerated polyethylene terephthalate

Methods

Agglomerated secondary PET was selected as the polymer matrix to create CM. Polyethylene terephthalate is a synthetic linear thermoplastic polymer that belongs to polyesters. It is characterized by [8] good heat resistance in the temperature range from 233 to 423 K, resistance to shocks and deformations, acids, alkalis, lubricants and most organic compounds.

Basalt roving (BR) (manufacturer is PrJSC "Research Institute of Fiberglass and Fiber" (RIFF, Ukraine)) was chosen as a filler for secondary PET. It was later cut to a size of 3 - 4,5 mm. Technical characteristics of BR are given in table 1 [9].

Table 1

Properties of basalt roving

Indicator	Value
Density, kg/m^3	2700
The average diameter of the unit fiber, μm	13,6
Linear density of a complex thread, tex	170
Breaking load of roving (not less), N (kgf)	500 (50)
Operating temperature, K	23 - 923
Chemical resistance (weight loss,% after three hours of boiling) in:	
- H_2O	1,6
- 2NaOH	2,75
- 2NHCl	2,2
Thermal conductivity coefficient, W/m ·K:	
- at 398 K	0,064
- at 573 K	0,096

Preparation of basaltoplastics (BP) on the basis of secondary PET containing 5 - 10 mass.% of BF was carried out in several stages. Thorough drying of PET was carried out to remove residual moisture (permissible amount was 0,02 - 0,5 %). It was done, because the further processing of undried PET at elevated temperatures leads to partial hydrolysis of the chains and, as a consequence, the irreversible deterioration of the physical, chemical and thermal properties of the polymer. Drying was carried out at 408 K in SPT-200 thermal cabinet for 3 hours. Mixing (combination) of the components was carried out in the apparatus under the influence of a rotating electromagnetic field (0,12 T) using ferromagnetic particles that were then removed from the composition by the method of magnetic separation. Pre-prepared prepregs were loaded into a mold heated to 383 K, then they were heated to 533 K and kept at this temperature for 15 minutes without load. Next, the samples were cooled under constant load (40 MPa) to a temperature of 383 K and removed from the mold.

Tribotechnical characteristics in the conditions of friction without lubrication according to the "disk-pad" scheme were studied on the SMC-2 friction machine at a load of 1,0 MPa, sliding speed of 0,5 - 1,5 m/s. Steel 45 (45 - 48 HRC, Ra = 0.32 μm) was used as a counterbody. The roughness of the samples was measured on 170621 profilometer using a sharp solid needle (probe), which moved on the surface of basaltoplastics and polyethylene terephthalate copying its irregularities. Studies of the friction surface morphology of the developed BP were performed using "BIOLAM-M" microscope. The hardness of PET and basaltoplastics based on it was determined using TD-42dynamic hardness tester [10].

Results

Analyzing the results of tribological studies, it was found that the basalt fiber reinforcement of secondary agglomerated PET leads to a decrease in the coefficient of friction (Fig. 1) and the intensity of linear wear (Fig. 2) by 1,5 and 4,5 times, respectively, reaching minimum values at the filler content 5 mass.%.

It can be seen from Fig. 1 that $f(\upsilon)$ dependence is extreme, that is, in the initial period the coefficient of friction increases with increasing sliding speed, and then, reaching its maximum value, gradually decreases [11]. The increase in the coefficient of friction in the range of speeds of 0,5 - 1,0 m/s is due to the increase of the friction force in the contact zone due to the frictionality of the BF. Further decrease of this indicator at a speed of 1,5 m/s can be explained by the fact that the sample volume is dominated by the processes of destruction (brittle fracture) due to the development of defects (pores, cracks) at the "PET - basalt fiber" interface. This is confirmed by the fact that the intensity of linear wear increases sharply (see Fig. 2) at υ = 1,5 m/s [12].

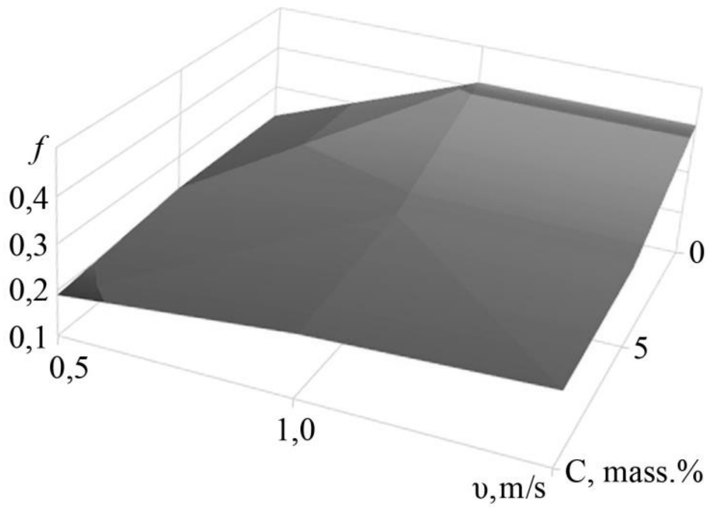


Fig. 1. Dependence of the friction coefficient of pure polyethylene terephthalate and basaltoplastics based on it on the sliding speed (specific load *P* = 1 MPa)

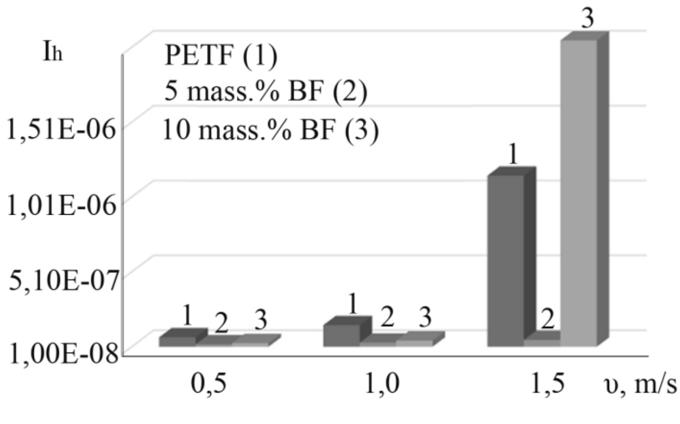


Fig. 2. Dependence of the intensity of linear wear of polyethylene terephthalate and basaltoplastics based on it on the sliding speed (specific load *P* = 1 MPa)

As for the temperature in the contact zone (see Fig. 3), it was found that the introduction of basalt fiber leads to its growth by an average of 15 %. This can be explained by the fact that the basalt fiber has a low thermal conductivity (see table 1) and, as a consequence, insufficient temperature removal from the contact zone. Reducing the temperature can be achieved by introducing fillers with high thermal conductivity. They can be: graphite, nickel, aluminum, copper, carbon and organic fibers.

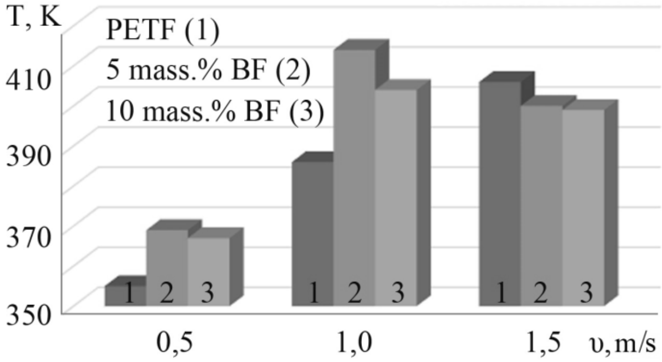
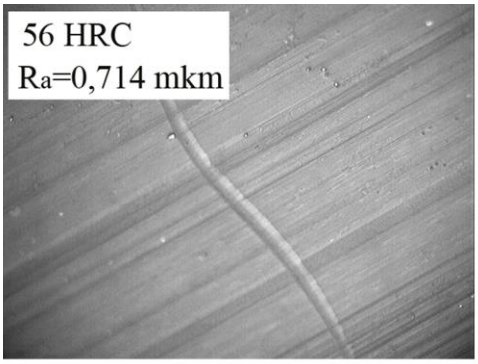
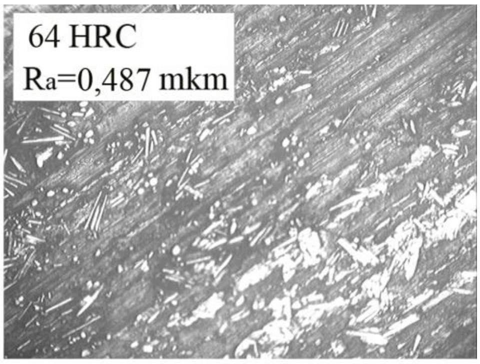


Fig. 3. Dependence of temperature in the contact zone of polyethylene terephthalate and basaltoplastics based on it on the sliding speed (specific load *P* = 1 MPa)

The study of the morphology of the friction surfaces showed (Fig. 4) that the introduction of basalt fiber reduces the depth of abrasion tracks by 40% (roughness of BP). Strengthening of BP is due to the fact that basalt fibers due to high technical characteristics complicate the movement of dislocations in the polymer binder under the action of the applied load. Confirmation of this is an increase in the hardness of polyethylene terephthalate by 15 %.



a



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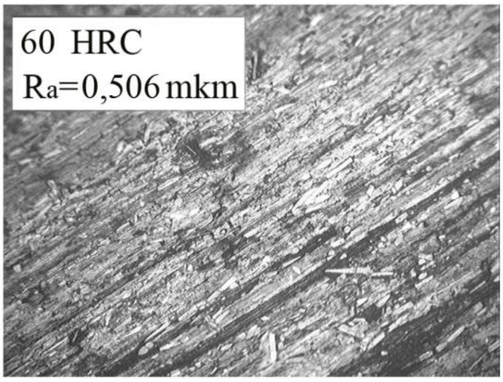

c

Fig. 4. Microstructure (× 100) of the friction surface during wear of polyethylene terephthalate (a) and basaltoplastics based on reinforced with 5 (b) and 10 (c) mass.% of fibers (specific load *P* = 1 MPa, sliding speed υ = 1 m/s)

From the above data it can be seen that the tribological properties and hardness improve only when the BF content is 5 mass.%, and with its further increase to 10 mass.% there is a sharp decline due to the growth of defects in the volume of the composite. This is confirmed by the fact that the calculated density of basaltoplastics (Fig. 5) containing 5 mass.% of fiber is less than the experimental density, and at 10 mass.% of fiber it is higher than hydrostatic one [13].

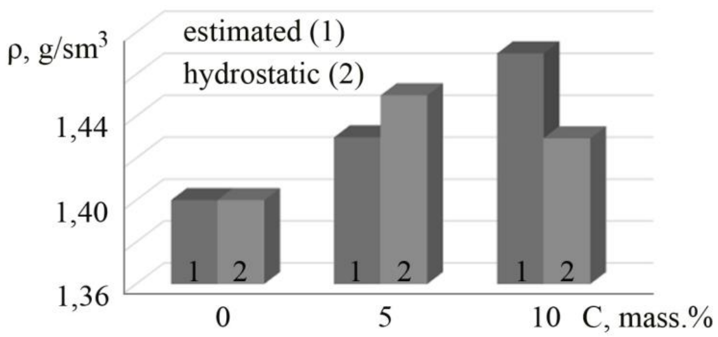

Fig. 5. Dependence of calculated and hydrostatic density of polyethylene terephthalate on the content of basalt fiber

This can be explained by the fact that at a basalt fiber content of 5 mass.% the process of ordering polyethylene terephthalate prevails over loosening at the "matrix - fiber" interface, and at a content of 10 mass.% it is vice versa.

Conclusions

Analysis of the results of the research (tribological and physico-mechanical) of the developed CM showed that the use of discrete basalt fiber as a filler for secondary PET is a promising way to increase wear resistance by 4,5 times and reduce the coefficient of friction by 50 %. BP with effective filler content was recommended for the manufacture of plain bearings for automotive, agricultural and metallurgical industries.

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Томіна А.-М.В., Єрьоменко О.В., Макаров В.С. Вплив базальтового волокна на трибологічні властивості вторинного поліетилентерефталату.

Зростання обсягів споживання композиційних матеріалів, зокрема триботехнічного призначення, в багатьох галузях сучасної промисловості потребує розробки нових зносостійких матеріалів, здатних до тривалої експлуатації. Використання твердих побутових відходів для виготовлення композиційних матеріалів, зокрема поліетилентерефталату, дозволяє отримати ряд переваг: екологічний аспект, попит споживачів і низьку вартість сировини. У статті розглянуто вплив дискретного базальтового волокна на трибологічні властивості вторинного агломерованого поліетилентерефталату в умовах тертя без змащення за схемою «диск-колодка». Встановлено, що введення наповнювача призводить до зменшення коефіцієнту тертя та інтенсивності лінійного зношування вихідного полімеру в 1,5 та 4,5 рази відповідно, сягаючи мінімальних значень при вмісті базальтового волокна 5 мас.%. Отримані результати обумовлені тим, що поява базальтового волокна зміцнює полімерну матрицю, а це в свою чергу підтверджує зростання твердості на 15 % і гальмує розвиток тріщин на поверхні композиту (шорсткість зменшується на 40 %). Дослідження температури в зоні контакту показало її збільшення, що зумовлено низьким показником теплопровідності наповнювача (0,064 - 0,096). В результаті цього в зоні тертя відбувається накопичення теплоти. Подальше збільшення волокна (до 10 мас.%) призводить до різкого погіршення трибологічних і фізико-механічних властивостей базальтопластиків, що спричинено зростанням дефективності матеріалу. Визначено, що ефективний вміст наповнювача в полімерній матриці складає 5 мас.%. Внаслідок чого даний композит був рекомендований для виготовлення деталей рухомих з’єднань аграрної, автомобільної та металургійної техніки.

Ключові слова: поліетилентерефталат, базальтове волокно, коефіцієнт тертя, інтенсивність лінійного зношування, температура в зоні контакту, твердість, шорсткість.

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E-mail: tribosenator@gmail.com

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Theoretical research of the technology of finishing cylinders with antifriction materials

D.D. Marchenko*, K.S. Matvyeyeva

Mykolayiv National Agrarian University, Mykolayiv, Ukraine
**E-mail: marchenkodd@mnau.edu.ua*

Abstract

The article analyzes the research aimed at the use of various materials, additives and additives to oils. It is established that their application is mainly limited to the stages of operation, bench and operational running-in. The use of antifriction materials at the stage of processing the parts of internal combustion engines, limiting the resource, is small, despite the fact that such treatment reduces the running-in time and improves the finish of the friction surfaces. Theoretical calculation of the parameters of the working surface of the engine cylinder liner during their finishing using special antifriction materials showed a 2-fold increase in the bearing surface (from 0.2 to 0.4 of the nominal surface area at the level of the middle line of the profile) and a roughness of 0.27 µm, which is close to the values after the bench run-in. This proves the possibility of using this treatment in order to reduce the time of preparation of CNG and improve the characteristics of the surfaces to be worked. It is established that the finishing of engine cylinder liners with antifriction materials should be carried out at the contact pressure of the working tool (brass bars) on the surface of the sleeve 3 MPa, the speed of the working tool 5.5 m/s, the processing time of the sleeve 20 min. Finishing of sleeves with use of compositions TSK-B100 + SURM-KV, SURM-UO and RVS allows to reduce mechanical losses on friction in TsPG by 5-19% at the beginning of process of running in after processing in comparison with mechanical losses at the end of cold running in without finishing sleeves; to obtain the roughness parameters after finishing the same as after cold running in without additional processing of the sleeves; increase the bearing surface by 2 - 2.5 times (from 0.2 - 0.25 to 0.4 - 0.5 of the nominal surface area at the level of the middle line of the profile), which confirms the calculated data. The final treatment of sleeves with compositions based on antifriction materials TSK-B100 + SURM-KV, SURM-UO and RVS allows to provide values of parameters of a working surface of sleeves (reduction of roughness, increase of a basic surface) approaching their values after cold running in, therefore allows to increase contact loadings. in the connection "sleeve - piston ring" after this treatment and reduce the time of the bench run-in (to the values required for the attachment of other engine connections).

Key words: finishing, wear resistance, friction reduction, antifriction materials, nanocompositions, resource.

Introduction

One of the factors that determine the durability of engines is the condition of the friction surfaces. It is known that wear resistance depends on the finishing (final) technological treatment of the surfaces of parts. There are experimental studies on the effect of roughness of friction surfaces on the intensity of wear. For widespread joints, the optimal values of roughness parameters have been identified, at which wear of parts is minimal. It is established that not only the primary (running-in) wear, but also constant wear depends on finishing of details, ie primary finishing can influence intensity of wear at long operation of cars. First of all, this applies to the parts of the cylinder-piston group (CPG) of internal combustion engines. When forming friction surfaces, it is necessary to ensure the optimal tribotechnical characteristics of the mating surfaces, such as low coefficient of friction, high wear resistance, optimal physical and mechanical properties. To a large extent, they are determined by the methods of treatment of friction surfaces. Recently, new technological processes of finishing have been developed, which allow to reduce running wear and increase antifriction properties (increase the lubrication of parts, reduce the coefficient of friction, etc.), as well as reduce the time of friction pairs [1].

However, the analysis of information obtained from printed and electronic sources makes it possible to state that not all reserves of intensification of CPG production processes in terms of application of new methods of finishing cylinder liners are exhausted.

Recently, the market for a variety of antifriction materials, additives and additives in oils, which form protective films on friction surfaces, is developing rapidly. The possibility of using such drugs to provide the working surfaces of the sleeves with optimal tribotechnical characteristics at the stage of their final processing in the repair or manufacture of internal combustion engines has been little studied [2]. Therefore, the influence of the treatment of cylinder liners with different antifriction materials in the repair or manufacture of internal combustion engines on the characteristics of working surfaces and processes of making connections is a relevant topic for research.

Literature review

Operating conditions of agricultural machinery reduce the service life of engines, which is largely determined by the service life of cylinder liners. Wear resistance and serviceability of cylinder liners depend on the quality of their working surfaces, which, in turn, is due to a combination of characteristics of roughness and corrugation, physical, mechanical and chemical properties, as well as the microstructure of the surface layer. The quality of the inner surfaces of the sleeves is formed in the process of performing a set of technological operations, taking into account the manifestation of technological heredity. Especially important are the finishing operations, as a result of which the main characteristics of the surface layer are finally formed.

Many scientists have studied the processes of making friction surfaces during the running-in of internal combustion engines, methods of processing the working surfaces of CPG parts, and the application of various antifriction materials. The following authors devoted their scientific works to these topics: S.G. Arabyan, V.I. Balabanov, N.S. Zhdanovsky, V.F. Karpenkov, V.S. Kombalov, V.N. Kuzmin, V.N. Listovsky, I.A. Mishin, V.S. Nekrasov, S.A. Ovodov, L.I. Pogodayev, G. Polzer, V.N. Popov, E.V. Ryzhov, V.V. Striltsiv, V.I. Tsyptsin and many others [3, 4].

The analysis of the conducted researches shows that, despite a very large number of works devoted to quality improvement and reduction of time of finishing of surfaces of the rubbing engines, some questions demand the further studying. In particular, little research has been presented on the application of new methods of finishing cylinders based on various antifriction materials in order to intensify the processes of LNG production [5].

Despite the achieved level of development of traditional methods of finishing cylinders of internal combustion engines (ICE), their application in agricultural repair practice is associated with considerable complexity, and the use of the most advanced technological processes is unable to meet modern requirements for quality cylinders and holes. to increase their reliability and durability [6]. In this regard, there is a need to develop a new method of finishing the cylinder liners using a tool design available to agricultural repair companies and provides the necessary characteristics of the surface layer.

Purpose

The purpose of the research is to improve the processes of CPG production by applying the finishing of cylinder liners with antifriction materials.

Research methodology

When the contact surfaces slide, first the process of attachment takes place, which is accompanied by a change in the microgeometry, as a result of which some constant roughness characteristic of these friction conditions is established. In the process of finishing, the physical and mechanical properties of the surface layers also change, because the contact is usually dominated by plastic deformations. Therefore, based on the initial microgeometry and the initial properties of the surfaces, it is possible to determine the contact characteristics only in the initial period of attachment. The process of finishing can be considered as a gradual increase in the bearing surface and the elastic component of the contact area, reducing the proportion of plastic, resulting in reduced total wear.

The process of finishing can be assessed by changing the reference curve. The reference curve characterizes the distribution of material along the height of the rough layer and plays an important role in calculating the area of rough bodies. According to N.B. Demkin and I.V. Kragelskiy initial part of the reference curve can be represented as:

$$t_p = \frac{\sum \Delta l_p}{l} = \frac{A_p}{A_c} = b\left(\frac{a}{R_{\max}}\right)^{v}, \tag{1}$$

where t_p – is a parameter of the relative reference length of the profile;

$\sum \Delta l_p$ – the total length of the sections of the protrusions at the level of p, mm;

l – base length of the profile, mm;

A_p – cross-sectional area of the protrusions at the level of p, mm^2;

A_c – nominal area, mm;

b and v – are the coefficients of static approximation of the reference curve (obtained by appropriate processing of surface profiles);

a – is the distance from the line of protrusions to the level of the section, μm;

$R_{\max}$ – maximum height of profile irregularities, μm.

Dependence (1) well approximates the initial section of the reference curve (to the middle line of the roughness profile).

The approximate values of the parameters of the roughness of the sleeve at different stages of its processing and running-in, used to calculate the reference curve, are presented in table. 1, which is compiled according to V.S. Kombalov, E.V. Ryzhov and S.A. Ovodov, as well as obtained during previous experiments [7].

Table 1

The value of the parameters of the roughness of the sleeve to calculate the reference curve

Processing stage	$R_{\max}$, μm	R_a, μm	r, μm	b	v
After honing	4,7	0,65	15	0,7	1,8
After finishing with special drugs	2,4	0,27	30	1,4	1,7
After the bench run-in	2,3	0,25	35	2,0	2,0

Research results

In Fig. 1 presents the calculated values of the initial section of the reference curve.

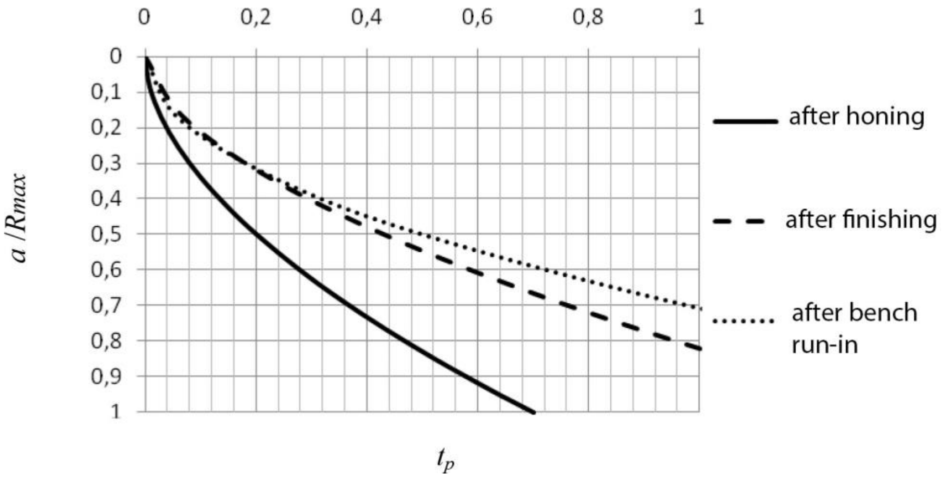

Fig. 1. Estimated values of the initial section of the reference curve

Also, the process of finishing can be assessed by changing the roughness parameters. For cylinder liners of the D-240 engine the normative and technical documentation normalizes the parameter R_a (arithmetic mean deviation of the profile).

According to L.E. Hallstani change of the arithmetic mean deviation of the R_a profile during surface finishing occurs according to the hyperbolic law:

$$Ra(t) = \frac{k \cdot Ra_H}{t \cdot Ra_H + k}, \quad (2)$$

where $Ra(t)$ is the arithmetic mean deviation of the profile, which varies depending on the wear time, μm;

$Ra_{н}$ – the initial value of the arithmetic mean deviation of the profile, μm;

t – time of preparation, h;

k – coefficient depending on the time of attachment [8].

Using the empirical Bosch formula $f = \dfrac{k}{1 + c \cdot v}$, the coefficient k was expressed:

$$k = f \cdot \left(1 + c \cdot v\right), \tag{3}$$

where f – is the coefficient of sliding friction (dimensionless), with time f decreases and for different times of attachment t will be different; c is the coefficient (for metals c = 3÷4);

v – is the speed of the piston, m/s (accepted speed v = 3.36 m/s).

The data obtained by S.A. Ovodov were used to calculate the coefficient of friction during the running-in of the CHP and the change in the intensity of wear during the running-in [9].

After conducting preliminary laboratory tests, the dependences of the coefficient of friction f on the time of attachment for different methods of processing the working surface of the sleeves were derived. At the initial coefficient of friction f = 0.1 on the oil M-10G2 were obtained dependences of the coefficient of friction during running after honing f_x and after finishing with antifriction materials $f_ф$ from time t.

$$f_x = 0{,}1006 - 0{,}0414 \cdot t + 0{,}0246 \cdot t^2 - 0{,}0050 \cdot t^3 \tag{4}$$

$$f_ф = 0{,}0691 - 0{,}422 \cdot t + 0{,}0343 \cdot t^2 - 0{,}0089 \cdot t^3 . \tag{5}$$

Suppose formulas (4) and (5), as well as the value c = 3.5 and v = 3.36 m/s in the fallowness (3), and then the formula in the fallowness (2) is taken away, the bullets neglected the formulas for the size of $Ra(t)$:

$$Ra_x = \left(t / \left(1{,}183 - 0{,}487 \cdot t + 0{,}289 \cdot t^2 - 0{,}059 \cdot t^3\right) + 1 / Ra_{нх}\right)^{-1}; \tag{6}$$

$$Ra_ф = \left(t / \left(0{,}813 - 0{,}496 \cdot t + 0{,}403 \cdot t^2 - 0{,}105 \cdot t^3\right) + 1 / Ra_{нф}\right)^{-1}, \tag{7}$$

where Ra_x, $Ra_ф$ – the average arithmetical view of the profile, which changes fallowly during the hour of growth, when used for honing and processing with antifriction materials of microns [10].

Deposits (6) and (7) are shown graphically in Fig. 2 at: cob value for the reduction of fine grain processing $Ra_{нх}$ = 0.65 microns, cob value for the reduction of fineness processing with antifriction materials $Ra_{нф}$ = 0.27 microns.

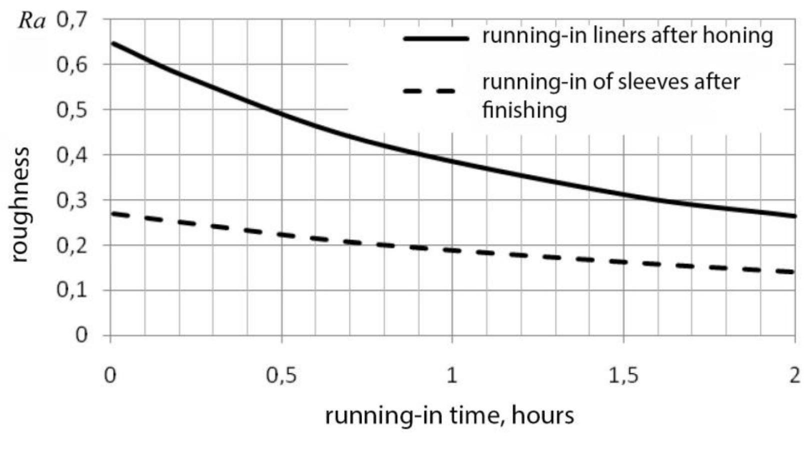

Fig. 2. The prevalence of the mean arithmetic output to the profile at the hour of growth

Conclusions

Calculation and theoretical analysis of the process of making cylinder liners allowed us to draw the following conclusions:

- finishing of cylinder liners increases the bearing surface by 2 - 2.5 times (see Fig. 1), while the values of the reference curve after finishing are close to its values after the bench run-in CPG;
- coefficient of friction and roughness at the beginning of the process of CPG preparation in the case of pre-treatment of sleeves with antifriction materials, equal to the values of these parameters at the end of the bench running of CPG in the case of sleeves after honing (see Fig. 2);
- since the intensity of wear is directly proportional to the coefficient of friction and pressure in the friction pair, the finishing of antifriction materials reduces the running-in wear, which affects the durability of the sleeves;
- based on the above, it can be argued that the finishing of the cylinder liners with antifriction materials can intensify the process of finishing CPG, which is expressed in reducing the hour of running and running-in wear.

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Марченко Д.Д., Матвєєва К.С. Теоретичні дослідження технології обробки циліндрів антифрикційними матеріалами.

В статті приведено аналіз досліджень, спрямованих на застосування різних матеріалів, добавок і присадок до масел. Встановлено, що їх застосування в основному обмежується етапами експлуатації, стендової і експлуатаційної обкатки. Застосування антифрикційних матеріалів на етапі обробки деталей двигунів внутрішнього згорання, лімітуючих ресурс, мало, не дивлячись на те, що така обробка дозволяє скоротити час проведення обкатки і поліпшити прироблення поверхонь, що труться. Теоретичний розрахунок параметрів робочої поверхні гільзи циліндра двигуна при їх фінішній обробці із застосуванням спеціальних антифрикційних матеріалів показав збільшення опорної поверхні в 2 рази (з 0,2 до 0,4 від номінальної площі поверхні на рівні середньої лінії профілю) і отримання шорсткості 0,27 мкм, що близько до значень після стендової обкатки. Це доводить можливість застосування цієї обробки з метою зменшення часу приробленні ЦПГ і поліпшення характеристик поверхонь, що приробляються. Встановлено, що фінішну обробку гільз циліндрів двигуна антифрикційними матеріалами слід проводити при контактному тиску робочого інструменту (латунних брусків) на поверхню гільзи 3 МПа, швидкості робочого інструменту 5,5 м/с, часу обробки гільзи 20 хв. Фінішна обробка гільз із застосуванням композицій ТСК-В100+СУРМ- КВ, СУРМ-УО і РВС дозволяє понизити механічні втрати на тертя в ЦПГ на 5-19% на початку процесу обкатки після обробки в порівнянні з механічними втратами у кінці холодної обкатки без фінішної обробки гільз; отримати параметри шорсткості після фінішної обробки такі ж, як після холодної обкатки без додаткової обробки гільз; збільшити опорну поверхню в 2 - 2,5 разу (з 0,2-0,25 до 0,4-0,5 від номінальної площі поверхні на рівні середньої лінії профілю), що підтверджує розрахункові дані. Остаточна обробка гільз композиціями на основі антифрикційних матеріалів ТСК-В100+СУРМ-КВ, СУРМ-УО і РВС дозволяє забезпечити значення параметрів робочої поверхні гільз (зменшення шорсткості, збільшення опорної поверхні) що наближаються до їх значень після холодної обкатки, отже дозволяє збільшити контактні навантаження в сполученні "гільза - поршневе кільце" після цієї обробки і зменшити час стендової обкатки (до значень, необхідних для приробленння інших сполучень двигуна).

Ключові слова: фінішна обробка, зносостійкість, зменшення тертя, антифрикційні матеріали, нанокомпозиції, ресурс.

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Theoretical justification of the influence of change of dilaton and compression bonds of atoms of materials of machine parts on their tribological effect

V.V. Aulin[1*], S.V. Lysenko[1], A.V. Hrynkiv[1], O.D. Derkach[2], D.O. Makarenko[2], I.V. Zhylova[1]

[1]*Central Ukrainian National Technical University, Ukraine*
[2]*Dniprovsky State Agrarian-Economic University, Ukraine*
**E-mail: AulinVV@gmail.com*

Abstract

The course of friction and wear processes in the surface layers of conjugations of machine parts is clarified on the basis of the idea of dilaton and compression bonds of atoms in the materials of parts. Dilaton-compression connections are random in nature, and therefore in this work the theory of destruction of parts by S.M. Zhurkov, thermodynamic and quantum physical approaches. The entropy at the macro-, meso- and microscopic levels and the local regions of the materials of conjugation of the parts subject to friction loading are considered. In the diagram of the state of atomic-molecular bonds the dependence curve $F_i(r_i)$ or $T_i(r_i)$ is considered and the analysis of transformations of bonds according to the specified diagram is carried out. From the point of view of solid state physics and tribophysics, the manifestation, evolution and consequences of the influence on the characteristics and properties of the friction zone of dilaton and compression bonds of material atoms are considered. Composite materials (composite coatings) are substantiated in more detail. This takes into account the assessment of the concept of material stresses in the friction zone, the ability to relax it, as well as the presence of the SD effect. The fracture process is associated with the modulus of elasticity of the components of the composite material and the bulk content of the filler. An appropriate condition is proposed, which determines the tribological efficiency of composite materials and coatings.

Key words: dilaton and compression connections, state diagram, entropy, fracture, composite material (coating), SD-effect, stress concentration.

Introduction

Increasing the intensity of load application to the materials of conjugations of parts, assemblies and units of machines determines the speed of their deformation, increasing the stress state and changing the tensile strength [1]. Under such conditions, the behavior, characteristics and properties of parts, local areas of their materials and work surfaces differ significantly. The nature of the processes of friction and lubrication that occur in the surface layer of parts is multifactorial. The micro-impact load in the process of collision of abrasive particles and wear particles with the working surfaces of parts, friction, as well as the destruction of the material is determined by its impact strength and strength [2, 3]. The behavior of the material of parts in such conditions is primarily determined by the following factors: the structure and properties of the material of parts; composition, properties and wear capacity of the working environment; the magnitude and nature of the load of external forces; their distribution, etc. [4, 5, 6].

The destruction of the materials of tribocouples of parts during operation has a thermofluctuation nature [7, 8]. For crystalline materials, an active specific change in the state of their surface layers under load has been established: from nanostructuring to amorphization, intensive dislocation processes to the formation of cracks, and so on.

Literature review

The kinetics of friction and wear of materials in tribophysics is considered at the atomic-molecular level, taking into account the state of the electronic subsystem of materials under load. Mechanical loading of the surface of materials leads to perturbations in the electronic subsystem, and the rupture of interatomic bonds means a sharp excitation of electronic states. In the kinetics of wear, the interlevel transition of processes is important. The results of detailed studies of the properties of the surface layers of materials indicate a close connection between mechanical processes and electronic ones. The nature and characteristics of the phenomena of wear of surface layers can be substantiated by tribophysical methods on the basis of the proposed methodology [9].

The operational wear resistance of most parts and working bodies depends on their working condition and the complex of physical-mechanical and operational properties of the working surfaces of the parts [9, 10, 11, 12, 19]. Their failure is primarily due to the size and nature of wear, as well as fatigue of the material.

Purpose

The purpose of this work is to clarify the possibility of using the theory of destruction of materials of parts S.M. Zhurkov and ideas about local areas of compression and dilaton connections, to explain the state and behavior of the material in the friction zone of the conjugation of parts, components and units of machines.

Results

During operation, the transition of materials of tribocouples of parts in the contact zone from nonequilibrium to equilibrium, the formation of micro-, meso- and macroformation in it depends on the formation of electromagnetic dipoles of local areas of dilaton or compression connections between them and their mutual transition. According to the theory of S.M. Zhurkov, from the point of view of thermodynamics [13, 14, 15, 16], the state of the *i*-th local region of the material of the part can be described by the equation:

$$P_i dV_i = T_i dS_i \,, \tag{1}$$

where P_i – is the load in the *i*-th local region with a volume of dV_i, which causes the formation of residual stresses;

dS_i – change in entropy associated with the development of defects in the structure of materials (internal entropy);

T_i – thermodynamic temperature;

$i = \overline{1, n}$.

Entropy is a general characteristic of irreversible thermodynamic changes observed in the material and have a macro-, meso- and microscopic nature. Macroscopic changes in entropy determine the formation of cracks, dents, streaks, porosity, scratches, various transitions from geometric shape, and others. Mesoscopic changes in entropy are due to the ability of the structure of the structural material of the parts to phase transitions. Microscopic changes in entropy are an indicator of the degree of perfection of the material structure of machine parts. They need to take into account both the number of atomic-molecular bonds and their energy evaluation.

According to quantum solid state physics (SSP), based on Debye's theory, there is a directly proportional relationship between microscopic entropy and the number of atomic-molecular bonds and their relative energy:

$$S_i = k_B N_{i\,bon} \delta_i \,; \tag{2}$$

$$\delta_i = -\frac{9}{8}\frac{\theta_i}{T_i} + 1 - 3\ln\frac{\theta_i}{T_i} + \frac{\pi^4}{5}\left(\frac{T_i}{\theta_i}\right)^3 , \tag{3}$$

where k_B – became Bora;

$N_{i\,bon}$, δ_i – respectively, the number and coefficient of relative energy of atomic-molecular bonds;

T_i, θ_i – respectively thermodynamic and characteristic temperatures in the i-th region.

The state of interatomic or molecular bonds is determined by the local temperature T_i and the free energy F_i in this region. The condition of the material of the part is significantly affected by the processes occurring at the microscopic level. Because the critical change in the material is the formation of microcracks in it, which are associated with the destruction of the crystal lattice.

The diagram of the state of atomic-molecular bonds of local regions of the material is graphically represented by the curve dependence $F_i(r_i)$ and $T_i(r_i)$ (fig. 1), which consists of a depression (acceleration pit) and a ridge (brake barrier).

The ratio of these thermodynamic temperatures is as follows:

$$T_b > T_f > T_d\ . \tag{4}$$

Let us analyze the state diagram of atomic-molecular bonds in the local region of the friction zone, in the surface layer of conjugation details (fig. 1).

In the local region of the acceleration cavity (brake hole), state diagrams $(r_1,\ r_2)$ form dilaton types of bonds in the material, and in the local region of the brake barrier $(r_2,\ r_3)$ – compression types. From the point of view of SSP, the type of bond is characterized by the directions of spins of atoms (molecules) in the nodes of the crystal lattice of the material [26, 28]: for dilatons spins are parallel, which causes electrostatic repulsion of atoms (molecules) and back, which leads to the appearance of forces of attraction and the creation of local areas of compression deformation.

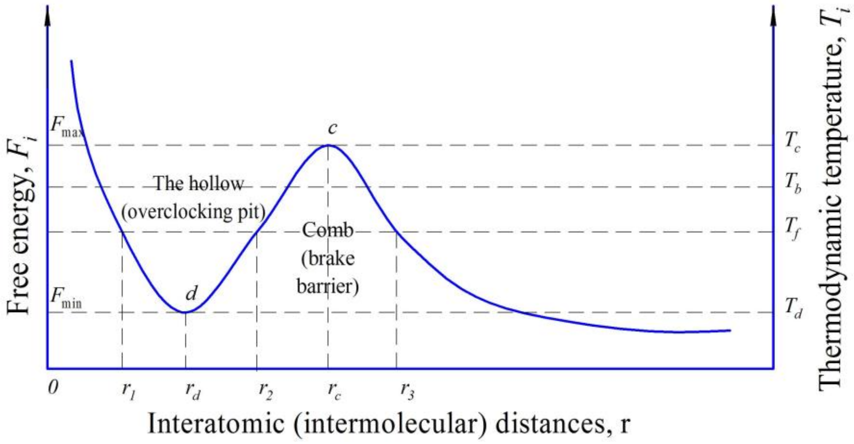

Fig. 1. Diagram of the state of atomic-molecular bonds of local regions of the material as a function of free energy and thermodynamic temperature from the interatomic (intermolecular) distance:
T_d – the minimum thermodynamic temperature in the depressions, which is characteristic of the dilatonic type of bonds of atoms or molecules;
T_b – thermodynamic equilibrium temperature;
T_f – phase transition;
T_c – the maximum thermodynamic temperature in the ridge is characteristic of the compression type of connections

From the diagram of the state of atomic-molecular bonds it can also be seen that dilaton bonds are formed in the low-temperature region with a minimum of free energy, and compression – in the high-temperature region with a maximum of free energy. When phonons are emitted by compresses, the local temperature of the material decreases and it passes into the dilaton region, while the dilaton region cannot pass into the compresson region. Under the influence of friction loading in the dilaton regions of the materials of conjugations of parts there is a fragile deformation and destruction, and in the compression, during their transition to the dilaton region - plastic. Of course, these processes are random. At their imposing the whole macroregions of brittle or plastic deformation, and also directions of development and distribution of microcracks in surface layers of material of details can be observed.

It was found that metals and alloys capable of phase transformations (PT) [5, 17, 18] have mainly atomic bonds of the compression type, while abrasive materials and solid fillers in composite materials have mainly dilaton bonds. type. Based on the SSP, compresses and dilatons have an electromagnetic nature and are electromagnetic dipoles. The flow of AF in the materials of parts indicates their role as energy characteristics of the crystal lattice nodes, which in the process of friction and wear of the material go into nonequilibrium, and in the transition to steady state dipoles emit a stream of electromagnetic wave energy [20]. Under the action of an external load or the influence $\vec{A}_{PT}$ of a physical field, the state of dipoles changes with intensity. Dipoles perpendicular to the direction of the external field $\vec{A}_{PT}$ emit phonons and the temperature of the local region approaches Td, and in the planes in which the dipoles are located along the field, the bonds absorb phonons at

$T \Rightarrow T_c$, increasing the size of the local regions of the material.

The nonequilibrium state in the local region of the material of the part during friction is described by the equation:

$$p_i V_i \left(dV_i / V_i + dp_i / p_i \right) = k N_{i\,bon} T_i \delta_i \left(dN_{i\,bon} / N_{i\,bon} + dT_i / T_i + d\delta_i / \delta_i \right), \tag{5}$$

in which the deviation from equilibrium is due to deformation dV_i / V_i and changes in load resistance dp_i / p_i and is accompanied by a decrease in the number of connections $dN_{i\,bon} / N_{i\,bon}$, thermal radiation dT_i / T_i and disruption of energy connections $d\delta_i / \delta_i$. The nature of the friction processes is determined primarily by the strength of the flux of atomic-molecular bonds in the local regions of the material.

Static and dynamic tension in this case causes a reduction in the cross-sectional area of the material near the fracture site, because $N_{T_c} > N_{T_d}$. Note that with tired wear $N_{T_c} \approx N_{T_d}$. The fracture surface usually has two zones: the actual fatigue fracture, which is formed due to the decay of the dilaton type of bonds at temperature T_d, and the final fracture at temperature T_c of the compressor type of bonds. The duration of stable existence of atomic-molecular bonds of local regions of the material is determined by the range of thermodynamic temperatures (T_c, T_d), which does not exceed 15 … 20 % of the full temperature range [16]. At critical temperatures T_c or T_d, the bonds are destroyed and energy is emitted in the form of a pulse:

$$q_1 = k_B \delta\,; \quad q_2 = (k_{\hat{A}} / h_P)\, \Delta r m \delta^2, \tag{6}$$

where h_P – is the Planck constant (h_P = 6,62·10^{-34} J·s);

m – is the mass of interacting atoms.

If the difference in thermal deformation of the inhomogeneous material or matrix and filler in the composite material when the temperature changes by ΔT is $\delta_{\text{т}}$, then in the local areas of significant inhomogeneity or matrix with a shear modulus G_m around each filler particle there are stresses, the maximum values of which reach $2G_m \delta_{\text{ò}}$ and can cause plastic deformation.

When the macrodeformation corresponding to the yield strength of the composite material $\sigma_{\text{т}}$, shear stresses are concentrated due to flat clusters of dislocations of local regions of inhomogeneity either in the composite material and the coating around or in front of the filler particles [21, 27]. This leads to a decrease in reverse stress and an increase in stresses in the main clusters of dislocations. In this regard, new flows of dislocations are generated, and existing dislocations pass along the plane of sliding at a distance much greater than L_n. The value of the yield strength is:

$$\sigma_{\text{т}} = \sigma_{\text{тм}} + \sqrt{G_m G_n \vec{b}_B / 2 L_n \xi_n}\,, \tag{7}$$

where G_m, G_n – shear modules of the matrix material and filler particles;

ξ_n – numerical coefficient, $\xi_n \approx 30$ [21, 26];

$\sigma_{\text{тм}}$ – yield strength of the matrix material. This is true for dispersed materials, when the maximum level of hardening of parts is achieved provided: $d_n = 2G_m b_B / \sigma_{\text{тм}}$. If $d_n \le 2G_m b_B / \sigma_{\text{тм}}$, then the radius of curvature of the dislocation $r_0 = 4b_B$ can not be neglected [27] and the yield strength of the composite material is equal to:

$$\sigma_{\text{т}} = \sigma_{\text{тм}} + G_n c_n^{\frac{1}{3}} \Bigg/ 4c_n \left(0{,}82 - c_n^{\frac{1}{3}} \right), \tag{8}$$

where c_n – is the volumetric content of the filler.

In parts reinforced with composite materials and coatings, the SD-effect can be observed [21], which consists in the appearance of micropores in the vicinity of the filler particles during tensile deformation and their absence during compression deformation. If the connection between the components of the material and the coating is strong, the dislocations are repelled from the boundary of their separation. If a micropore is present, the dislocation is attracted to the interface between the filler particle and the matrix. When the matrix is strengthened by solid particles of spherical filler [22, 23, 24], the maximum concentration of tensile stresses is on the surfaces of these particles. At uniaxial tension ($\sigma_{Np} > 0$), we have:

$$\sigma_{Np}/\sigma_p = 2/(1+\mu_{cm(cc)}) + 1/(4-5\mu_{cm(cc)}), \tag{9}$$

where σ_{Np} – is the tensile stress on the surface of the filler particle at points with coordinates ϑ = 0 and ϑ = 180°;

σ_p – applied tensile stress;

$\mu_{cm(cc)}$ – Poisson constant of the composite material, and at a compressive stress of $\sigma_{Np} < 0$, we obtain:

$$\sigma_{Nc}/\sigma_c = (1-\mu_{cm(cc)})/(1+\mu_{cm(cc)}) - (5-5\mu_{cm(cc)})/(8-10\mu_{cm(cc)}) . \tag{10}$$

If the interfacial boundary does not have sufficient strength, then the concentration of tensile stresses can cause its local destruction. This determines the presence of SD-effect, the manifestation of which is influenced by: the ratio of the modulus of elasticity of the matrix and the filler; chemical interaction at the interface of material components; correspondence of their crystal lattices; volume content of filler; test speed and temperature. When compressing stresses, such a concentration is not observed and the interface is not destroyed. Increasing the temperature increases the ability of the material to relax internal stresses and at some value the stress concentration will be lower than the strength of the interface of the material components, in which case there will be no breaks and SD-effect at the filler-matrix boundary.

V.I. Trefilov and V.F. Moiseev [25] identified two main factors influencing the nature of the destruction of disperse-strengthened materials: the strength of the interfacial boundary and the plasticity of the matrix. In this case, a qualitative characteristic of the strength of the interfacial boundary in the material may be the presence or absence of SD-effect: if SD = 0, the interfacial boundary is strong and does not collapse to $\sigma_{\text{т}}$, and if SD > 0, the interphase boundary collapses even in the elastic local region.

To assess the plasticity of the matrix of the composite material in the friction zone and the ability to relax the stress concentration, you can use parameter K_p [21]:

$$K_p = (G_n - G_m)/(G_n + G_m) . \tag{11}$$

Studies show that the smaller the value of $K_{пл}$, the lower the level of stress concentration in the region of dislocation clusters, and for the interface between brittle and plastic local regions of materials – K_p = 0,3 [25].

Given the value of K_p and the presence or absence of SD-effect, we have the following groups of materials reinforced with composite materials and coatings:

– fragile matrix and weak interfacial boundary (K_p < 0,3, SD > 0);

– plastic matrix and weak interfacial boundary (K_p > 0,3, SD > 0);

– brittle matrix and strong interfacial boundary (K_p < 0,3, SD = 0);

– plastic matrix and strong interfacial boundary (K_p > 0,3, SD = 0).

In each of these groups of materials, the filler particles (strengthening phase) play a different role in inhibiting the movement of cracks [8, 9]. Cracks can form both inside the filler particles and on the interface. The test results [10, 23] show that the cracks tend to be located perpendicular to the direction of maximum tensile deformation. J. Gerland [29, 30] proposed two theoretical models of the destruction of filler particles: the mechanisms of loading and accumulation of dislocations. According to the first model, the increase in stresses in the filler particles is associated with the shape or coefficient of their shape. The modulus of elasticity of the material $E_{cm(cc)}$ is within:

$$E_m E_n / [(1-c_n)E_n + c_n E_m] \le E_{cm(cc)} \le (1-c_n)E_m + c_n E_n . \tag{12}$$

The left part of inequality (12) means that the filler and the matrix are equally stressed, and the right - that they are equally deformed. Note that the particle size of the filler does not affect the modulus of elasticity of the composite material (composite coating) $E_{cm(cc)}$, if the coefficient of thermal expansion (CTE) of the matrix and the filler are almost equal. At the same time, if the CTE are different, cracks may appear around the larger filler particles $E_{cm(cc)}$. The shape of the filler particles does not affect the value of $E_{cm(cc)}$, if the particles are not oriented in the composite material. When the filler content is $\tilde{n}_n$ > 0,3, especially if the filler is fine, pores may form in the composite material and the value of $E_{cm(cc)}$ will decrease [10, 11].

This indicates that the particles of the filler of the composite material depends on both strengthening and destructive effects. They can be the initiators of cracks that occur under load of friction, and large particles are more dangerous than fine ones. If cracks do not occur in the composite materials, then controlling the modulus of elasticity of the components E_n and E_m , you can influence the size and nature of the strengthening of the materials of the parts, in their tribological efficiency.

Conclusions

1. The use of the theory of S.M. Zhurkov for the description of tribophysical processes in local regions of conjugations of details of knots of systems and units of machines on the basis of the diagram of a condition of atomic and molecular communications of them with dilaton and compression thermodynamic temperatures.
2. It was found that dilaton bonds are formed in the low-temperature region with a minimum of free energy. If phonons are emitted during tribophysical processes, the compresses reduce the local temperature and the material passes into the dilaton region, while the dilaton regions cannot pass into the compression region. In the dilaton areas of the material there is a fragile deformation and destruction, and in the compression, in the transition to dilaton - plastic. It is revealed in which cases metals and alloys have dilaton and compression type of atomic-molecular bond of atoms.
3. Based on solid state physics, compresses and dilatons have an electromagnetic nature and are electromagnetic dipoles. Phase transformations in materials can be associated with the influence of external physical fields on the behavior of electromagnetic dipoles and changes in their state and orientation.
4. The material in the friction zone of the tribocouples of parts has a non-equilibrium state, the degree of non-equilibrium of which is determined by the relative values of deformation and load, change in the concentration of the number of bonds, relative intensity of thermal radiation and energy bonds.
5. For composite materials and coatings theoretically substantiated their behavior in the friction zone, the ability to relax the stress concentration K_p and the presence of SD-effect, using the theory of S.M. Zhurkov and the idea of electromagnetic dipoles. Taking into account the specified parameters the characteristic groups of the materials strengthened by composite materials and coverings are resulted, their characteristics concerning formation of cracks are given.

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Аулін В.В., Лисенко С.В., Гриньків А.В., Деркач О.Д., Макаренко Д.О., Жилова І.В. Nеоретичне обґрунтування впливу зміни ділатонних і компресонних зв’язків атомів матеріалів деталей машин на їх трибологічну ефективність.

З'ясовано протікання процесів тертя та зношування в поверхневих шарах спряжень деталей машин на основі уявлення про ділатонні і компресонні зв'язки атомів в матеріалах деталей. Ділатонно-компресонні зв'язки мають випадкову природу, а тому в даній роботі використано теорію руйнування деталей С.М. Журкова, термодинамічний та квантово-фізичний підходи. Розглянуто ентропію на макро-, мезо- і мікроскопічному рівнях та локальні області матеріалів спряження деталей, що підлягають навантаженню тертям. В діаграмі стану атомно-молекулярних зв'язків розглянуто криву залежності $F_i(r_i)$ або $T_i(r_i)$ та здійснено аналіз перетворень зв'язків згідно зазначеної діаграми. З точки зору фізики твердого тіла та трибофізики розглянуто прояв, еволюція та наслідки впливу на характеристики і властивості зони тертя ділатонних та компресонних зв'язків атомів матеріалу. Більш детально обґрунтовано композиційні матеріали (композиційні покриття). При цьому враховується оцінка концепції напружень матеріалу в зоні тертя, здатність релаксувати її, а також наявність SD-ефекту. Процес руйнування пов'язується з модулями пружності компонентів композиційного матеріалу та об'ємного вмісту наповнювача. Запропоновано відповідну умову, яка визначає трибологічну ефективність композиційних матеріалів та покриттів.

Ключові слова: ділатонні і компресонні зв'язки, діаграма стану, ентропія, руйнування, композиційний матеріал (покриття), SD-ефект, концентрація напружень.

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The influence of auger wear on the parameters of the dehydration process of solid waste in the garbage truck

O.V. Bereziuk[1], V.I. Savulyak[1], V.O. Kharzhevskyi[2]

[1]Vinnitsa National Technical University, Ukraine
[2]Khmelnytskyi National University, Ukraine
E-mail: berezyukoleg@i.ua

Abstract

The article is dedicated to the study of the influence of auger wear on the parameters of the dehydration process of municipal solid waste in the garbage truck. An improved mathematical model of the drive operation of dehydration of solid waste in the garbage truck is proposed, which takes into account the wear of the auger and allowed to numerically determine the dynamics of the drive during start-up. It was also established that increasing wear of the auger, the pressure of the working fluid at the inlet of the hydraulic motor rises, and the angular velocity and speed of the auger is significantly reduced. The research of this mathematical model was carried out using the numerical Runge-Kutta-Felberg method of the 4^{th} order with a variable integration step. By means of the method of regression analysis, the power dependencies of the change of nominal values of pressures at the inlet of the hydraulic motor, angular velocity and speed of rotation of the auger from the value of its wear are determined. The last-mentioned dependence defines the detuning from the optimal speed of the auger during its wear and is used to determine the energy consumption of dehydration of solid waste, taking into account the wear of the auger. It is established that the wear of the auger by 1000 μm leads to an increase in the energy consumption of dehydration of solid waste by 11.6%, and, therefore, also leads to an increase of the cost of the process of their dehydration in the garbage truck. It was also established the expediency of further research to determine the appropriate material of the auger and the ways to increase its wear resistance.

Key words: wear, auger press, garbage truck, dehydration, solid waste

Introduction

One of the important tasks in machine building is the increasing the wear resistance and reliability of machine parts. Dehydration of municipal solid waste, which is accompanied by their pre-compaction and partial grinding, during loading into the garbage truck is a promising technology for their primary processing, aimed at reducing both the cost of transportation of solid waste and the negative impact on the environment. Dehydration of solid waste in the garbage truck is carried out by means of the conic auger, its surface undergoes an intensive wear due to the friction. This is due to the fact that solid waste contains, in particular, components such as metal, glass, stones, ceramics, bones, polymeric materials, which can be attributed to abrasive materials, because they have different shapes, sizes and hardness. The presence of moisture in the amount of 39-92% in solid waste creates an aggressive corrosive environment. Therefore, the study of the influence of auger wear on the parameters of the process of dehydration of solid waste in the garbage truck is a topical task.

Literary review

The results of experimental studies of wear resistance of different materials of auger with different thermal and chemical-thermal treatment in a corrosive-abrasive environment on special friction machines that simulated the operating conditions of extruders in the processing of fodder grain with saponite mineral impurities are given in the article [2].

Comparative studies have shown that the wear resistance of materials in a corrosive-abrasive environment at elevated temperatures depends not only on the hardness of the friction surface, but also on its structure and phase composition and changes in the hardness gradient along the depth of the hardened layer. To ensure high wear resistance of extruders in the manufacture of animal compound feed with impurities of the mineral saponite, it is recommended to use steel X12 strengthen by nitro-hardening technology for the manufacture of parts of the extrusion unit.

A mathematical model for calculating the wear rate of triboelements in a tribosystem which operates in the conditions of corrosion and abrasive wear was developed in the paper [3]. Input factors are active acidity, abrasiveness, roughness, load and sliding speed. Theoretically, the degree of influence of the above factors on the wear rate is established. Abrasiveness is the most important factor, and, by the decrease of influence – the level of active acidity and the load.

In the article [4], it was found that the intensity of abrasive wear of the screw surface of the auger, and hence wear resistance, mainly depends on the hardness, surface roughness, the volume of abrasive particles involved in friction and the area of their contact with the surface.

To restore the auger, it is necessary to process fusing or spraying a layer of a certain thickness on the end part of the auger coil, and the width of the restored layer is usually a few millimeters [5]. An algorithm for selecting the optimal composite powder material for plasma spraying in order to increase the wear resistance of the working surfaces of machine parts, in particular the auger, is described. The authors state that plasma spraying of composite powder materials will increase the durability of the auger by 2-3 times, which will reduce repair costs by tens of times.

The article [6] presents a new design of the auger with a sectional elastic surface, which is designed to reduce the degree of damage to the grain material during transportation. Theoretical calculation of grain interaction with elastic section of auger is carried out. A dynamic model has been developed to determine the influence of structural, kinematic and technological parameters of the elastic auger on the time and path of free movement of bulk material particles during their movement between sections, as well as to exclude the possibility of grain material interaction with the non-working surface of the auger working body to diminish its damage

The paper [7] is dedicated to the analysis of the process of auger briquetting of plant materials into fuel and feed. Dependencies of this process are the basis for determining the rational parameters of the working bodies. When designing briquette presses, it is necessary to consider the deformation of biomass taking into account the change in physical and rheological properties at the time of interaction with the auger mechanism.

The influence of geometric parameters on the performance and design of the briquetting machine was studied in the paper [8] using a pressure model based on the theory of piston flow. An analytical model that uses a pressure model was also developed based on Archard wear law to study the wear of augers of biomass briquetting machines. The developed model positively predicted the wear of the auger and showed that the greatest influence on it are the speed of rotation and the choice of material. The amount of wear increases exponentially to the end of the auger, where the pressure is the highest. Changing the design of the auger to select the optimal geometry and speed with the appropriate choice of material can increase the service life of the auger and the productivity of the machine for briquetting biomass.

The process of pressing wood chips in auger machines is researched in the article [9]. The processes occurring in different parts of the auger are established, also were defined the formulas that allow to calculate the loads acting on the auger turns, as well as to determine the power required for pressing. The specific energy consumption and the degree of heating of raw materials during pressing are also defined.

The wear of a twin-auger extruder of rigid PVC resins was researched in the article [10]. The pressures around the cylinder when extruding two rigid PVC resins in a laboratory extruder with a diameter of 55 mm were measured and the forces acting on the screw core were determined. Numerical modeling of the flow was performed using the power parameters of the viscosity of the resins.

In the paper [11] the results of experimental studies of the process of solid dehydration based on the planning of the experiment by the Box-Wilson method are shown. Quadratic regression equations with 1st order interaction effects were obtained using rotatable central composite planning for such objective functions as humidity and density of pre-compacted and dehydrated municipal solid waste, maximum drive motor power, energy consumption of solid waste dehydration. This allowed to determine the optimal parameters of equipment for dehydration by the criterion of minimizing the energy consumption of the process (frequency of auger speed, the ratio of the radial gap between the auger and the housing, and the ratio of the diameter of the auger core to the outer diameter of the auger on the last coil) both for mixed and “wet” solid waste. The obtained experimental dependences allowed to build a mathematical model of the drive of dehydration of solid waste in the garbage truck [12], which allowed to study the dynamics of this drive and the influence of control parameters on the main indicators of the drive. But this mathematical model and experimental dependencies do not take into account the wear of the auger, so, it requires further research.

Purpose

The aim of the article is to research of the influence of auger wear on the parameters of the dehydration process of municipal solid waste in a garbage truck.

Methods

To study the mathematical model of the drive of dehydration of solid waste in a garbage truck taking into account the wear of the auger in the form of a system of ordinary nonlinear differential equations with corresponding boundary conditions, the numerical Runge-Kutta-Felberg method of the 4th order with variable integration step was used [13].

To determine the paired dependencies of change of nominal pressure values at the inlet of the hydraulic motor, angular velocity and speed of rotation of the auger from the values of its wear, the method of regression analysis was used [14]. Regression analysis was performed on the basis of linearizing transformations, which allow to transform the nonlinear dependence to the linear one. The determination of the coefficients of regression equations was carried out by the method of least squares using the developed computer program "RegAnaliz", which is protected by copyright law and appropriate certificate, as described in the paper [15].

Results

In the Fig. 1 a calculation scheme of the drive of dehydration of solid waste in the garbage truck is shown, the following elements and parameters are designated: HM – hydromotor, TR – throttle, P – hydraulic pump, OV – overflow valve, F – filter, T – tank with working liquid, p_1, p_2, p_3 – pressures respectively at the pump outlet, at the inlet of the hydraulic motor, at the outlet of the hydraulic motor; W_1, W_2, W_3 – pipe volumes between pump and throttle, throttle and hydraulic motor, hydraulic motor and filter; Q_H – actual pump feed; S_{TR} - the area of the throttle hole, S_F – the surface area of the filter element; q_M – working volume of the hydraulic motor; J – the moment of inertia on the shaft of the hydraulic motor; M_T – torque of technological loading on a shaft of the hydraulic motor; ω – angular velocity of the hydraulic motor shaft.

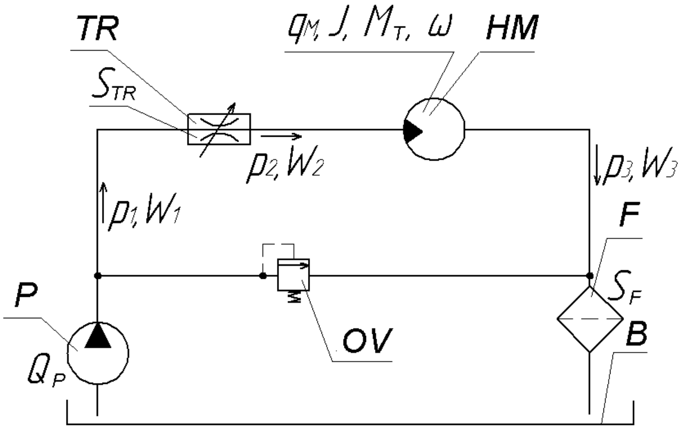


Fig. 1. Calculation scheme of the drive of dehydration of solid waste in garbage truck

The operation of the solid waste dehydration drive in the garbage truck, taking into account the wear of the auger, can be described by the corresponding system of differential equations (1–4) with the boundary conditions (5) and the algebraic equation (6):

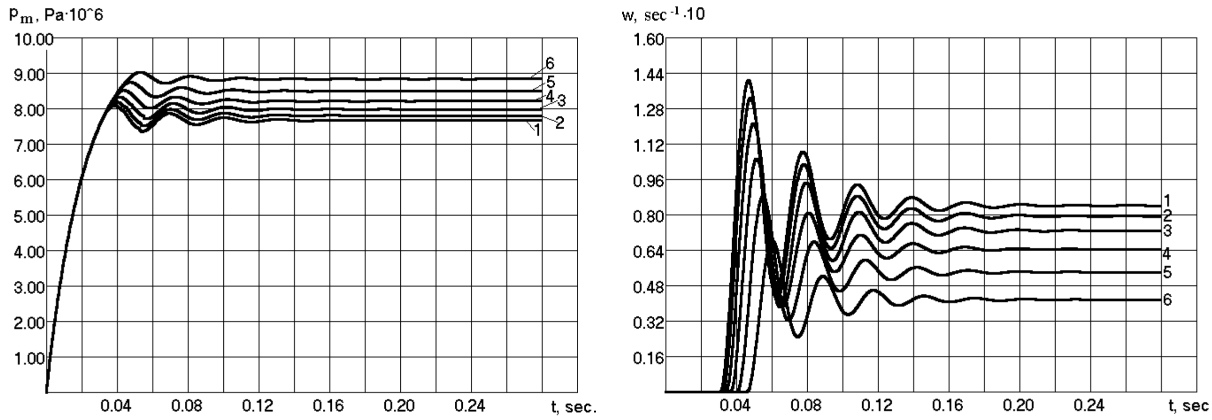
$$
\begin{cases}
Q_P = \mu S_{TR}\sqrt{2\left(p_1 - p_2\right)/\rho} + \sigma\left(p_1 - p_2\right) + KW_1\dot{p}_1; & (1) \\
\mu S_{TR}\sqrt{2\left(p_1 - p_2\right)/\rho} = q_{MX}\omega + \sigma\left(p_2 - p_3\right) + KW_2\dot{p}_2; & (2) \\
q_{MX}\omega = k_F S_F p_3/\mu_D + \sigma p_3 + KW_3\dot{p}_3; & (3) \\
q_{MX}\left(p_2 - p_3\right) = \{L_{aug}\rho_0(\overline{T} + 2u)^2[(\overline{D} - 2u)^2 - (\overline{d} - 2u)^2]/(16\pi) + \pi\rho_{aug}[n_c(h - 2u)(\overline{D} - & \\
-\overline{d})[(\overline{D} - 2u)^2 - (\overline{d} - 2u)^2]\sqrt{\pi^2(\overline{D} + \overline{d} - 4u)^2 + 4(\overline{T} + 2u)^2} + L_c(\overline{d} - 2u)^4]/32\}\dot{\omega} + & \\
+\beta\omega + \alpha q_{MX}\left(p_2 + p_3\right) + 30\{12231 + 109.8w_0 - 0.7676\rho_0 + 27.45n + 91602(\Delta_{aug} + u)\div & \\
\div(D_{\min} - 2u) - 41610(d_{\min} - 2u)/(D_{\min} - 2u) - 0.2475w_0 n + 558.6w_0(\Delta_{ш} + u)/(D_{\min} - & (4) \\
-2u) - 260.9w_0(d_{\min} - 2u)/(D_{\min} - 2u) - 7.713\,\rho_0(d_{\min} - 2u)/(D_{\min} - 2u) - 165174\times & \\
\times[(\Delta_{aug} + u)/(D_{\min} - 2u)][(d_{\min} - 2u)/(D_{\min} - 2u)] + 0.7082\,w_0^2 + 0.009383\rho_0^2 - 0.0726\times & \\
\times n^2 + 40815[(d_{\min} - 2u)/(D_{\min} - 2u)]^2\}/(\pi n); &
\end{cases}
$$

$$0 \le \{p_1, p_2, p_3\} \le p_{ov};\ 0 \le \omega; \tag{5}$$

$$q_{MX} = q_M /(2\pi), \tag{6}$$

where L_{aug} – the length of the auger, m; ρ_0 – the initial density of the solid waste, kg/m^3; $\overline{T}$ – the average pitch of the turns of the conical auger, m; u – wear of the auger, m; $\overline{D}$ – the average outer diameter of the auger; $\overline{d}$ – the average diameter of the screw core, m; ρ_{aug} – the density of the auger material; n_c – the number of coils of the auger; h – coil thickness; L_c – auger core length, m; w_0 – the initial relative humidity, %; n – nominal auger speed, rpm; Δ_{aug} – radial clearance between the auger and the housing, m; D_{min} – outer diameter of the auger on the last turn, m; d_{min} – diameter of the core of the auger on the last turn, m; q_{MX} – radial working volume of the hydraulic motor, m^3.

The results of the numerical study of the mathematical model (1–6) are shown in the Fig. 2, where the numbers 1-6 denote the curves that correspond to such values of screw wear: 0, 150, 300, 450, 600, 750 μm, in accordance. As shown in the Fig. 2, with increasing wear of the auger the pressure of the working fluid at the inlet of the hydraulic motor, but the angular velocity and the speed of the auger are significantly reduced.



a) b)

Fig. 2. Transient processes in the drive of solid waste dehydration during start-up: a) pressure at the inlet of the hydraulic motor; b) angular velocity of the auger

Nominal values of pressures at the inlet of the hydraulic motor, angular velocity and speed of rotation of the auger for different values of its wear are given in Table 1.

Table 1

Nominal values of pressures at the inlet of the hydraulic motor, angular speed and speed of rotation of the auger for different values of its wear

u, μm	0	150	300	450	600	750
$p_м$, MPa	7.763	7.794	7.972	8.202	8.485	8.825
ω, rad/sec	8.396	7.919	7.267	6.430	5.394	4.150
n, rpm	52.75	49.69	45.66	40.40	33.89	26.08

As a result of regression analysis of the data in Table 1, the power dependencies of the change of nominal values of pressures at the inlet of the hydraulic motor, angular velocity and speed of rotation of the auger from the values of its wear are determined:

$$p_m = 7.745 + 1.4 \cdot 10^{-5} u^{1.7}; \tag{7}$$

$$\omega = 8.348 - 2.033 \cdot 10^{-4} u^{1.5}; \tag{8}$$

$$n = 52.43 - 1.276 \cdot 10^{-3} u^{1.5}. \tag{9}$$

The correlation coefficient is 0.99955; 0.99968; 0.99968, correspondently, which indicating the sufficient convergence of the results.

In the Fig. 3 are shown the graphical dependences of the nominal values of the pressure at the inlet of the hydraulic motor, angular velocity and speed of rotation of the auger on the value of its wear, plotted using dependences (7-9), so sufficient convergence of the obtained dependencies in comparison with the data in the Table 1 is confirmed.

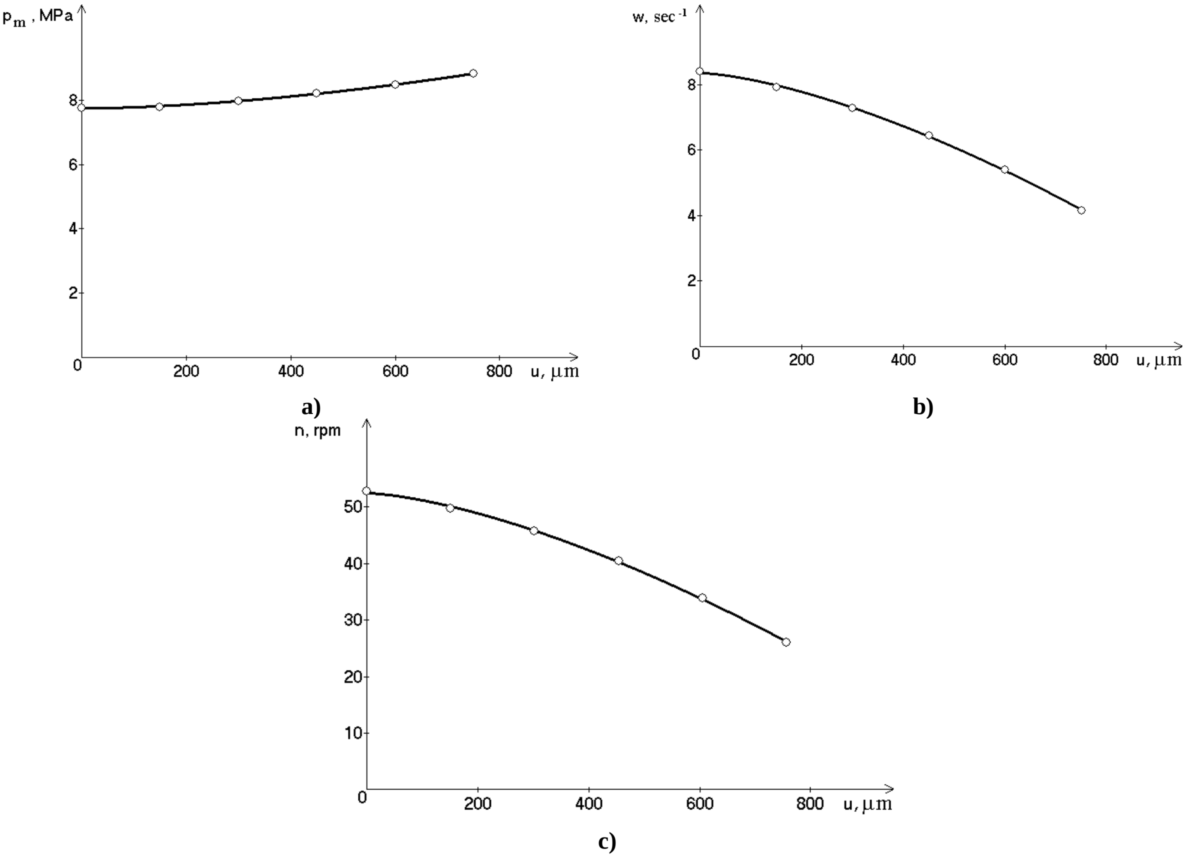


Fig. 3. Dependences of nominal values of pressures at the inlet of the hydraulic motor (a), angular velocity (b) the speed of rotation (c) of the auger from the values of its wear: actual ○, theoretical —

The dependence (9) describes the detune from the optimal speed of the auger in the process of its wear and is used to determine the energy consumption of solid waste dehydration taking into account the wear of the auger

$$E = 1504 - 15.92 w_0 + 0.3214 \rho_0 - 1.069 n(u) - 2061(\Delta_{aug} + u)/(D_{\min} - 2u) - 1947(d_{\min} -$$
$$- 2u)/(D_{\min} - 2u) + 9.118 \cdot 10^{-4} w_0 \rho_0 + 0.002142 w_0 n(u) + 18.12 w_0 (\Delta_{aug} + u)/(D_{\min} - 2u) -$$
$$- 2.115 w_0 (d_{\min} - 2u)/(D_{\min} - 2u) + 4.392 \cdot 10^{-4} \rho_0 n(u) - 2.005 \rho_0 (\Delta_{aug} + u)/(D_{\min} - 2u) + \quad (10)$$
$$+ 0.3361 \rho_0 (d_{\min} - 2u)/(D_{\min} - 2u) + 0.09031 w_0^2 - 7.923 \cdot 10^{-4} \rho_0^2 + 0.008241 n(u)^2 +$$
$$+ 104172 [(\Delta_{aug} + u)/(D_{\min} - 2u)]^2 + 1318 [(d_{\min} - 2u)/(D_{\min} - 2u)]^2 \; [\text{kW} \cdot \text{h/t}].$$

In the Fig. 4 is shown a graphical dependence of the increasing of energy consumption of solid waste dehydration due to the auger wear:

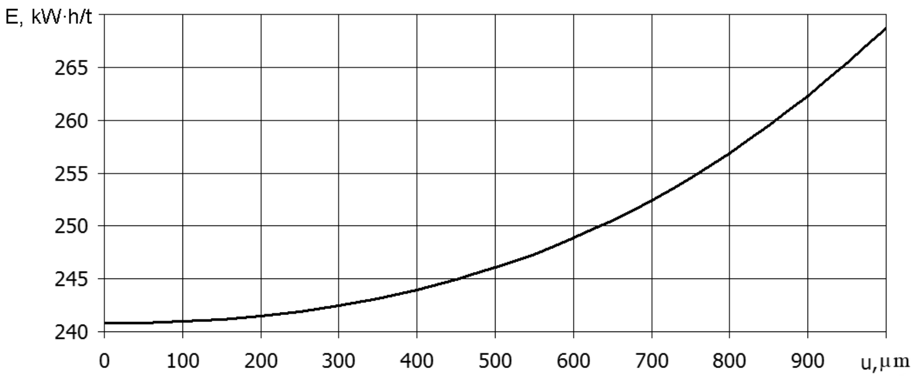


Fig. 4. Increase in energy consumption of solid waste dehydration due to the auger wear

As shown in the Fig. 4, the wear of the auger by 1000 μm leads to an increase in the energy consumption of solid dehydration by 11.6%, and, consequently, to an increase in the cost of the process of dehydration of solid waste in the garbage truck. In addition, it also leads to significant additional heat dissipation in the pressing area. This heat is mainly concentrated at the end of the working zone of pressing. The result is melting and coking of solid components, which converts them into abrasive particles. Consequently, in the auger material under the influence of significant temperatures and mentioned factors, phase transformations occur and catastrophic wear occurs.

Therefore, the definition of the rational material of the friction surfaces of the auger and the ways to increase its wear resistance require further researches.

Conclusions

An improved mathematical model of the operation of the drive of dehydration of solid waste in the garbage truck, taking into account the wear of the auger, which allowed to numerically research the dynamics of this drive during start-up and determine that with increasing wear of the auger, the pressure of the working fluid at the inlet of the hydraulic motor rises, but the angular velocity and speed of rotation of the auger are significantly reduced. The power dependencies of change of nominal values of pressures at the inlet of the hydraulic motor, angular speed and frequency of rotation of the auger from values of its wear are defined, the last of which describes detune from optimum frequency of rotation of the auger during its wear. That is used to determine the energy consumption of dehydration of solid waste, taking into account the wear of the auger. It is established that the wear of the auger by 1000 μm leads to an increase in the energy consumption of dehydration of municipal solid waste by 11.6%, and, consequently, to the increase in the cost of the dehydration process in the garbage truck and accelerate the wear process. Therefore, determining the rational type of material of the auger and the ways to increase its wear resistance require further researches.

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Березюк О.В., Савуляк В.І., Харжевський В.О. Вплив зносу шнека на параметри процесу зневоднення твердих побутових відходів у сміттєвозі

Анотація

Стаття присвячена дослідженню впливу зносу шнека на параметри процесу зневоднення твердих побутових відходів у сміттєвозі. Запропонована удосконалена математична модель роботи приводу зневоднення твердих побутових відходів у сміттєвозі, яка враховує знос шнека і дозволила чисельно дослідити динаміку даного приводу під час пуску та визначити, що зі збільшенням зносу шнека зростає тиск робочої рідини на вході гідромотора, а кутова швидкість і частота обертання шнека суттєво знижується. Дослідження даної математичної моделі проводилось за допомогою чисельного методу Рунге-Кутта-Фельберга 4-го порядку зі змінним кроком інтегрування. За допомогою використання методу регресійного аналізу визначено степеневі закономірності зміни номінальних значень тисків на вході гідромотора, кутової швидкості та частоти обертання шнека від величини його зносу, остання з яких описує відлагодження від оптимальної частоти обертання шнека в процесі його зносу і використана для визначення енергоємності зневоднення твердих побутових відходів із урахуванням зносу шнека. Встановлено, що знос шнека на 1000 мкм призводить до зростання енергоємності зневоднення твердих побутових відходів на 11,6%, а, отже, і до подорожчання процесу їхнього зневоднення у сміттєвозі. Виявлено доцільність проведення подальших досліджень з визначення раціонального матеріалу шнека та шляхів підвищення його зносостійкості.

Ключові слова: знос, шнековий прес, сміттєвоз, зневоднення, тверді побутові відходи.