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International scientific journal "Problems of Tribology",
Khmelnitsky National University,
Institutskaia str. 11, Khmelnitsky, 29016, Ukraine
phone +380975546925

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E-mail: tribosenator@gmail.com

Internet: http://tribology.khnu.km.ua

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Адреса редакції:
Україна, 29016, м. Хмельницький, вул. Інститутська 11, к. 4-401
Хмельницький національний університет, редакція журналу “Проблеми трибології”
тел. +380975546925, **E-mail**: tribosenator@gmail.com

Internet: http://tribology.khnu.km.ua

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

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E-mail: tribosenator@gmail.com

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Evaluation of tribological characteristics of technical oils with fullerene compositions

A.G. Kravtsov

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

Abstract

The paper presents experimental studies of the tribological characteristics of liquid lubricants of various viscosity classes and various groups of operation when using fullerene compositions. Tribological characteristics were evaluated on a four-ball friction machine according to GOST 9490.

The use of fullerene compositions in the form of a finely dispersed fullerene powder, pre-dispersed (dissolved) in vegetable high oleic oils, for example, rapeseed, with the subsequent addition of the resulting composition to technical oils of various viscosity classes and various groups of operation, leads to the following positive effect. The anti-wear properties of oils, which are assessed by the wear indicator, increase by 20,0…30,7 %, and the critical load on 18,8…25,0%. These indicators significantly exceed similar indicators when using fullerene fine powders without preliminary dispersion in vegetable oils, where the effect is on the border 11,1…15 %.

Fullerene additives do not affect the extreme pressure properties of base oils, which are assessed by the scuffing load. This result makes it possible to state that the way to improve the tribological properties of lubricants by introducing a fine powder of fullerenes into base technical oils is ineffective.

The experimental results obtained confirm the hypothesis about the possibility of the micelle formation mechanism in the lubricant under the action of the electrostatic field of the friction surface. The presence of a surfactant solvent (vegetable oil) allows you to "start" the micelle formation process at lower fullerene concentrations and to obtain the effect of increasing anti-wear properties.

Key words: fullerenes; vegetable oils; four-ball friction machine; tribological characteristics; critical load; welding load; bully index; technical oils.

Introduction

Today, the use of fullerenes is of great interest of C_{60}, as additives to liquid lubricants. In recent years, a number of scientific articles have appeared, where the results of studies of the effect of fullerene additives to lubricants on the processes of friction and wear of metals have been presented and a conclusion has been made about the prospects of using such additives.

An interesting and important feature of fullerene additives is that fullerenes are readily soluble in a wide class of organic and inorganic solvents. At the same time, poor solubility of fullerenes in technical oils was noted (mineral, semi-synthetic and synthetic). To date, the solubility of C_{60} in a large number of liquids has been determined and analyzed. It is shown that the solubility of fullerenes decreases with increasing polarity of the solvent. A number of unusual properties of fullerene solutions have been revealed, so for some solvents the effect of an anomalous dependence of the solubility of fullerene on temperature was found. At a temperature of about 280 ^{o}K maximum solubility is observed in these systems C_{60}, after which it starts to decrease.

Another interesting phenomenon observed in fullerene solutions C_{60}, are the processes of formation and growth of clusters, which indicate the proximity of many solutions C_{60} to the class of colloidal systems. The defining moment of this phenomenon is the fact that the size of the fullerene lies on the border of the definition concept of a colloidal particle (according to colloidal chemistry, colloidal particles range in size from one nanometer to several micrometers). The polarity of the solvent also has a great influence on this process.

The use of fullerene additives for technical liquid lubricants raises a number of questions about their effectiveness, i.e. influence on anti-wear and extreme pressure properties. Interest in this phenomenon is of both fundamental and applied nature, which will allow the development of concepts for their application.

Literature review

The authors of the work [1] provide an overview of the literature on lubricants with added nanoparticles. The effect of nanoparticles on the tribotechnical characteristics of oils has been analyzed. The paper notes that the use of nanoadditives to lubricants leads to an increase in the viscosity of the base medium, a high bearing capacity of the interface, a decrease in the friction coefficient, and an increase in wear resistance. Work [2] contains conclusions that the characteristics of a lubricant can be improved by using nanoadditives. Adding nanoparticles to conventional base oils is a promising direction. The work is devoted to an informative review of the application of nanoadditives to liquid lubricants and the prospects for its use in the production of oils. Similar conclusions about the prospects of using nanomaterials in liquid lubricants have been made by the authors of the work. [3].

Works [4-6] are devoted to fullerenes as additives to lubricants. The authors note that the use of fullerenes reduces the coefficient of friction and increases the wear resistance of mates. In work [6] it is noted that the concentration of the fullerene additive should be within 0,5…2,0% masses. In work [7] the result of using fullerene is given C_{60}. The authors note a positive effect, however, they conclude that the mechanism of the senergism of fullerenes with base oil is unclear and requires further research. At the same time, it was noted in the work that a decrease in the friction coefficient with the addition of fullerenes to oils can reach 90% compared to the base oil.

Analysis of works devoted to the use of fullerenes as additives to lubricants allows us to conclude that fullerenes are not dispersed (dissolved) in all technical oils [8-10]. This conclusion has been confirmed by the author of the work [11]. The introduction of fullerene additives in the form of a finely dispersed powder into technical oils of various viscosity classes and various groups of operation improves the anti-wear properties of oils, which are estimated by the wear indicator (increase by 11,1…15 %) and critical load (increase by 11,8…17,4%). Fullerene additives do not affect the extreme pressure properties of base oils, which are assessed by the scuffing load. This result makes it possible to state that the way to improve the tribological properties of lubricants by introducing a fine powder of fullerenes into base technical oils is ineffective. As follows from the above analysis of scientific works, such an insignificant effect is typical due to the intense clustering of fullerene molecules in the environment of industrial oils containing surfactants. Technical oils act as a highly polar solvent.

The experimental results presented allow us to conclude that it is necessary to develop other, more technological techniques and methods for introducing fullerene additives into technical lubricants, the theoretical justification of which has been developed in the works [12, 13]. In the presented works, a mathematical model of the interaction of electrically active heterogeneous fine-dispersed systems at the interface friction surface - lubricant has been developed. From the analysis of the solution of the differential equation, which describes the process of interaction of electric fields, it has been found that the introduction of fullerenes into the base lubricant does not bring a large effect.

It has been theoretically established that the use of fullerene "solvents", which can be high oleic vegetable oils, you can "start" the process of micelle formation, where the nucleus of the micelle is a fullerene molecule surrounded by molecules, for example, oleic or stearic acid. In work [12] theoretical studies that have shown, that the number of micelles is 50 times higher than the number of clusters in the base lubricating medium at the same concentration of fullerenes, and the dipole moment of micelles is an order of magnitude higher than the dipole moment of clusters. At the same time, micelles are more effective, where a single fullerene molecule acts as a nucleus, rather than a cluster of fullerene molecules, which affects the size of the formed micelles. The role of the friction surface on the formation of clusters and micelles in the lubricant film at the friction surface is established. It is shown that under the action of the stress-strain state of the surface layers, the friction surface acts as "Generator of electrostatic force field", which affects the formation of an electric field in the volume of the oil film. Expressions are obtained for calculating the value of the total electric field strength of the system "friction surface + lubricant".

In works [12, 13] it has been theoretically established that the electrostatic field of the friction surface is the driving force for the formation of an electrostatic field in the volume of the oil film, which is adsorbed on the friction surface. It shows that the process of cluster formation from fullerene molecules and micelles from fullerene molecules and fullerene solvent molecules affects the magnitude of the electrostatic field in the volume of liquid. Based on the review of publications and the performed modeling, it has been found that high oleic vegetable oil can act as a "strong solvent" of fullerenes.

Purpose

The purpose of this work is to carry out experimental studies of the tribological characteristics of liquid lubricants in the presence of fullerene compositions in their composition, which contain a fine powder of fullerenes, previously dispersed (dissolved) in vegetable high oleic rapeseed oil in various concentrations.

Methods

The tribological characteristics were assessed on a four-ball friction machine according to the method described in GOST 9490.

1. Fullerene compositions were prepared in the following mass concentrations. Base oils free from fullerene compositions.

2. Fullerene supplement 50 g/kg. It contains 0,5 g of fullerenes and 49,5 g of vegetable rapeseed oleic oil. Mass addition 50 g is introduced in 1000 g of base oil.

3. Fullerene supplement 100 g/kg. It contains 0,75 g of fullerenes and 99,25 g of vegetable rapeseed oleic oil. Mass addition 100 g is introduced in 1000 g of base oil.

4. Fullerene supplement 150 g/kg. It contains 1,0 g of fullerenes and 149,0 g of vegetable rapeseed oleic oil. Mass addition 150 g is introduced in 1000 g of base oil.

5. Fullerene supplement 200 g/kg. It contains 1,5 g of fullerenes and 198,5 g of vegetable rapeseed oleic oil. Mass addition 200 g is introduced in 1000 g of base oil.

6. Fullerene supplement 250 g/kg. It contains 2,0 g of fullerenes and 248,0 g of vegetable rapeseed oleic oil. Mass addition 250 g is introduced in 1000 g of base oil.

Experimental studies included the determination of tribological characteristics on a four-ball machine of liquid lubricants of the following operation groups:

- hydraulic mineral oil, by classification ISO corresponds to NM, viscosity class 10, trade mark MGP-10;
- engine oil, according to SAE 30 classification, API CC operation group, trade mark M-10G_{2k};
- gear oil, SAE 75W90 classification, API GL-5 service group, trade mark VALVOLINE.

Fullerenes in the form of fine powder of various concentrations F=0,5…2,0 grams “dissolved” in high oleic rapeseed oil and added to the above-listed technical base oils in the form of a fullerene composition (FK).

Results

In the process of experimental studies, the following tribological characteristics have been determined:
- wear rate, D_w, *mm*;
- critical load, P_{cr}, *N*;
- welding load, P_{weld}, *N*;
- bully index, I_b, *N*.

Experimental results for hydraulic oil MGP-10 are presented in the table 1, for engine oil M-10G_{2k} in the table 2, for transmission oil VALVOLINE GL-5 in the table 3.

The experimental results were checked for reproducibility by Cochran's criterion according to the formulas (1), (2):

$$G_p = \frac{S^2{}_{\max}}{\sum_{i=1}^{N} S^2{}_i}, \tag{1}$$

where S^2_{max}- maximum value of variance for D_w, P_{cr}, P_{weld}, I_b in accordance;

S_i^2- the value of the variance of the *i* - th experiment for D_w, P_{cr}, P_{weld}, I_b in accordance.

The hypothesis was tested:

$$G_p < G_{tab}, \tag{2}$$

where G_{tab} – tabular value of the Cochren's criterion, with a given confidence interval $q = 0,90$.

During the statistical processing of the experimental results, the number of repetitions of the same type was determined, which make it possible to ensure the experimental error at the level of confidence equal to $q = 0,90$.

The obtained experimental values allow us to conclude that tests on a four-ball machine of liquid lubricants for various purposes with different concentrations of fullerene compositions are reproducible and reliable under the condition of three repeats of the same type.

In tables 1 - 3 the arithmetic mean values of three repetitions of tribological characteristics are given.

Analysis of the data given in the tables 1 – 3 allows us to draw the following conclusions.

Wear indicator D_w increases by 20,0…30,7 %, at the same time, the larger value refers to the MGP-10 hydraulic oil, and the lower value refers to the transmission oil VALVOLINE GL-5. It follows from the tables that improvements in anti-wear properties for all oils are characteristic up to a concentration 150 g/kg in the base lubricant. If we compare with the data presented in the work [11], where a finely dispersed fullerene powder was used as an additive, then the wear index D_w increases by 11,1…15 %, at the same time, the improvement of anti-wear properties begins with a concentration of 0.2% masses, fullerenes in the lubricant.

Table 1

Tribological characteristics of hydraulic oil MGP-10 with the addition of fullerenes (F) and with fullerene composition (FC)

Lubricant	D_w, mm	P_{cr}, N	P_{weld}, N	I_b, N
MGP-10, HM	0,65	784	1568	24
MGP-10 + 0,05% F	0,6	784	1568	24
MGP-10 +50 g/kg FC	0,55	823	1568	26
MGP-10 + 0,1% F	0,6	823	1568	24
MGP-10 +100 g/kg FC	0,5	921	1568	28
MGP-10 + 0,15% F	0,6	872	1568	26
MGP-10 +150 g/kg FC	0,45	980	1568	30
MGP-10 + 0,2% F	0,55	921	1568	27
MGP-10 +200 g/kg FC	0,45	980	1568	30
MGP-10 + 0,3% F	0,55	921	1568	27
MGP-10 +250 g/kg FC	0,45	980	1568	30

Table 2

Tribological characteristics of M-10G$_{2k}$, API CC engine oil with the addition of fullerenes (F) and with fullerene composition (FC)

Lubricant	D_w, mm	P_{cr}, N	P_{weld}, N	I_b, N
M-10G$_{2k}$, API CC	0,45	1235	2450	28
M-10G$_{2k}$ + 0,05% F	0,45	1235	2450	28
M-10G$_{2k}$ + 50 g/kg FC	0,40	1235	2450	30
M-10G$_{2k}$ + 0,1% F	0,45	1235	2450	29
M-10G$_{2k}$ + 100 g/kg FC	0,35	1303	2450	32
M-10G$_{2k}$ + 0,15% F	0,45	1235	2450	30
M-10G$_{2k}$ + 150 g/kg FC	0,34	1381	2450	34
M-10G$_{2k}$ + 0,2% F	0,4	1303	2450	31
M-10G$_{2k}$ + 200 g/kg FC	0,33	1381	2450	34
M-10G$_{2k}$ + 0,3% F	0,4	1381	2450	31
M-10G$_{2k}$ + 250 g/kg FC	0,33	1381	2450	34

Table 3

Tribological characteristics of VALVOLINE GL-5 gear oil with the addition of fullerenes (F) and with fullerene composition (FC)

Lubricant	D_w, mm	P_{cr}, N	P_{weld}, N	I_b, N
GL-5	0,45	1960	4900	76
GL-5 + 0,05% F	0,45	1960	4900	76
GL-5 + 50 g/kg FC	0,40	2067	4900	82
GL-5 + 0,1% F	0,45	1960	4900	78
GL-5 + 100 g/kg FC	0,38	2195	4900	84
GL-5 + 0,15% F	0,45	2067	4900	80
GL-5 + 150 g/kg FC	0,36	2323	4900	88
GL-5 + 0,2% F	0,4	2195	4900	82
GL-5 + 200 g/kg FC	0,36	2323	4900	88
GL-5 + 0,3% F	0,4	2195	4900	82
GL-5 + 250 g/kg FC	0,36	2323	4900	88

The results obtained allow us to conclude that the concentration limit for the fullerene composition in industrial oils can be 100…150 g/kg. A further increase in concentration does not bring a positive effect.

The positive effect is also characteristic of the indicator – critical load P_{cr}, which characterizes the range of performance of anti-wear additives. The critical load is increased by 18,8…25,0%, the larger value refers to the hydraulic oil and the lower value refers to the transmission oil. At the same time, an increase in the critical load for all oils is characteristic up to a concentration 150 g/kg, in the base lubricant. If we compare with the data presented in the work [11], where a finely dispersed powder of fullerenes was used as an additive, then the critical load increases by 11,8…17,4%.

Changes in the value of the welding load P_{weld} during the experiments were not recorded, this allows us to conclude that the fullerene composition obtained by dissolving a fine powder of fullerenes in vegetable high oleic rapeseed oil does not improve the extreme pressure properties of liquid lubricants, but is only an antiwear additive.

Bully index I_b, which characterizes the integral tribological characteristic of the lubricant increases by 15,7…25,0%, the larger value refers to the hydraulic oil and the lower value refers to the transmission oil. In work [11], where a finely dispersed fullerene powder was used as an additive, it was noted that the bully index I_b increases by 7,8…12,5%.

The obtained experimental results confirm the [12, 13] hypothesis about the possibility of the mechanism of micelle formation in the lubricant under the action of the electrostatic field of the friction surface. The presence of a surfactant solvent (vegetable oil) allows «start» process of micelle formation at lower concentrations of fullerenes and to obtain the effect of increasing anti-wear properties on 20,0…30,7 %, while the dissolution of fullerenes in the base oil without the use of a solvent has the effect of increasing the anti-wear properties on 11,1…15%.

The obtained values of the improvement of antiwear properties coincide with the values obtained by other researchers, whose work is reviewed above.

Conclusions

The use of fullerene compositions in the form of a finely dispersed powder of fullerenes, previously dispersed (dissolved) in vegetable high oleic oils, for example, rapeseed, with the subsequent addition of the resulting composition to technical oils of different viscosity classes and different groups of operation, leads to the following positive effect. The anti-wear properties of oils, which are assessed by the wear indicator, increase by 20,0…30,7 %, and the critical load on 18,8…25,0%. These indicators significantly exceed similar indicators when using fullerene fine powders without preliminary dispersion in vegetable oils, where the effect is on the border 11,1…15 %.

Fullerene additives do not affect the extreme pressure properties of base oils, which are assessed by the bully load. This result makes it possible to state that the way to improve the tribological properties of lubricants by introducing a finely dispersed powder of fullerenes into base technical oils is ineffective. As follows from the above analysis of scientific works such an insignificant effect is typical due to the intense clustering of fullerene malecules in the environment of industrial oils containing surfactants. Technical oils act as a highly polar solvent.

The obtained experimental results confirm the [12, 13] hypothesis about the possibility of the mechanism of micelle formation in the lubricant under the action of the electrostatic field of the friction surface. The presence of a surfactant solvent (vegetable oil) allows you to «start» the micelle formation process at lower fullerene concentrations and to obtain the effect of increasing anti-wear properties.

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Кравцов А.Г. Оцінка трибологічних характеристик технічних олив з фулереновими композиціями

В роботі представлені експериментальні дослідження трибологічних характеристик рідких мастильних матеріалів різного класу в'язкості і різних груп експлуатації при використанні фуллеренових композицій. Трибологічні характеристики оцінювалися на четирьохкульковій машині тертя згідно ГОСТ 9490.

Використання фулеренових композицій у вигляді дрібнодисперсного порошку фулеренів, попередньо диспергированого (розчиненого) в рослинних високоолеінових оліях, наприклад, ріпакової, з подальшим додаванням отриманої композиції в технічні оливи різних класів в'язкості і різних груп експлуатації, призводить до наступного позитивного ефекту. Протизносні властивості олив, які оцінюються показником зносу, збільшуються на 20,0 ... 30,7%, а критичне навантаження на 18,8 ... 25,0%. Дані показники значно перевищують аналогічні показники при застосуванні фелеренових дрібнодисперсних порошків без попереднього диспергування в рослинних оліях, де ефект знаходиться на межі 11,1 ... 15%.

На протизадирні властивості базових технічних олив, які оцінюються навантаженням зварювання, фулеренові композиції не впливають. Такий результат дозволяє констатувати, що шлях поліпшення трибологічних характеристик мастильних матеріалів шляхом введення фулеренових композицій в базові технічні оливи є малоефективним.

Отримані експериментальні результати підтверджують гіпотезу про можливість механізму міцелоутворення в змащувальному матеріалі під дією електростатичного поля поверхні тертя. Наявність поверхнево-активного розчинника (рослинна олія) дозволяє «запустити» процес міцелоутворення при більш низьких концентраціях фулеренів і отримати ефект підвищення протизносних властивостей.

Ключові слова: фулерени; рослинні олії; чотирьохкулькова машина тертя; трибологічні характеристики; критичне навантаження; навантаження зварювання; індекс задира; технічні оливи.

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New approach to elucidating the physical nature of the processes that occur in the friction zone of mates of machine parts

V.V. Aulin, S. V. Lysenko, A.V. Hrinkiv, A.E. Chernai, I.V. Zhylova

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

Abstract

It has been found that during frictional contact in separate local areas of a thin surface layer of parts under significant loads and deformations and high contact temperatures, the material of the tribocontact zone of parts transforms into a special activating unstable state of magma-plasma or triboplasma. General issues in which the nature of the processes of friction and wear of mating parts is clarified are considered at a higher fundamental level with the involvement of nanotribology.

A number of processes that accompany interactions of triboconjugations of parts are analyzed: mechanoemission, mechanochemical, gas-discharge, etc., tribochemical reactions, fluxes of high-energy particles: excited molecules, atoms, ions, fast electrons, phonons (sound quanta and quanta of electromagnetic radiation).

Regularities of additivity of elastic and magnetic aftereffect in the volumetric parts and surface layers of tribo-interface parts made of ferromagnetic materials and alloys have been revealed. Also, the regularity of the additivity of the diffusion aftereffect in their surface layers has been established. A tribophysical model of self-organization is built on the basis of a carbon-nitrogen cycle of tribochemical reactions that have the content of thermonuclear fusion reactions and which can be considered at the nanoscale. In these reactions, the carbon atom plays the role of a catalyst for the process of fusion of protons with subsequent transformation into a radioactive isotope, which decays into ordinary carbon and helium. It has been established that the mechanism of nuclear fusion reactions in the surface layers of triboconjugation parts is due to the directional movement of dislocations in the crystal structures of materials with the implementation of the proton cycle and the conversion of hydrogen into helium.

It has been shown that this makes it possible to change the idea of the mechanocaloric effect, the process of friction and wear, and to substantiate a number of effects and processes from the physical positions of nanotribology. This will allow the creation of competitive tribotechnologies in various industries.

Key words: mating parts, friction criteria, wear resistance, reliability of systems and units

Introduction

The interaction in the movable interfaces of parts of systems and machine assemblies causes, first of all, the occurrence of processes of friction and wear, as well as the failure caused by them, amounting to about 90%. Losses from the processes of friction and wear in developed countries reach 5...6% of the national income. To overcome frictional resistance in machines and mechanisms, 20...25% of the energy generated per year is spent all over the world.

An increase in the economic and environmentally sound reliability of systems and assemblies of machines, technological equipment and tools is directly related to an increase in the wear resistance of resource-determining mates of parts. The solution to this urgent problem is possible only on the basis of deep scientifically grounded fundamental knowledge, the processes occurring in the surface layers of parts, and have a tribophysical nature and which can be substantiated at the levels: nano-, micro-, meso- and macrolevels.

Management of friction processes, the correct choice of materials for mating parts according to the criteria of friction and wear resistance, their rational design, as well as optimization of operating conditions can significantly provide a high level of operational reliability of machines and increase the efficiency of their use, reduce harmful environmental impacts with a slight increase in cost [1].

Academicians V.I. Kolesnikov, Yu.M. Luzhny, A.V. Chichinadze believed that the complex of studies in the field of macro-, meso-, micro- and nanotribology of triboconjugation of parts of systems and aggregates of transport machines in general refers to the main and topical areas of their operational reliability [2].

Literature review

I.V. Kragelsky, M.N. Dobychin, V.S. Kombalov [3], analyzing the critical points characterizing the conditions for the transition from one type of frictional interaction to another, argued that in some local areas of a thin surface layer of parts, significant stress and strain and high contact temperatures develop. In this case, the material of the contact zone of the parts passes into a special activating unstable state. This position of the material P.A. Thyssen is called magma-plasma or triboplasm [4]. Substances in the state of "triboplasma" are capable of reacting with materials of mating parts and the external environment. It is typical that a reaction is observed even with neutral substances, neutral gases.

A new interpretation of the mechanisms of thermoplastic deformation during the phase transformation of the materials of parts under nonequilibrium conditions and a significant temperature gradient is given in [5]. It is shown that in the friction zone the processes and states of materials self-organize. Positive self-organization in tribotechnical systems increases the efficiency of their functioning [6]. A physical approach to the mesomechanics of wear of the working surfaces of parts of tribocouplings [7,8] is considered and a scale-level approach to the analysis of the characteristics and properties of surface layers of parts and a lubricating medium is proposed [9]. It is noted that mesomechanics is a modern approach to the theory of wear [10]. The tribophysical material science approach is informative about the processes and states of materials, and the assessment of their resources [11]. From a physical point of view, the processes of friction and wear in the contact zone of the triboharness of parts of motor transport and agricultural machinery have been analyzed [12]. From the standpoint of fullerenes, their influence on the physical and mechanical properties of the friction surface of tribocouplings of parts has been clarified [13]. The physics of the formation of a stress-strain state makes it possible to clarify the formation of local areas of compression and tension deformations [14]. The electrochemical and mechanical loads on the tribocouplings of parts with the implementation of a whole range of phenomena and the improvement of tribocharacteristics are also of interest [15]. The essence of a new approach is to identify the physical nature of friction processes [16] with the construction of a physical model of tribological processes [17] and analysis of the processes of changing the states of materials in the tribosystem [18].

Analyzing the solution of general issues concerning nanotribology, Yu.I. Golovin [19] notes that the desire to identify and understand the nature of nanocontact processes of friction and wear of mating parts at a higher fundamental level is quite natural. The first step in this direction is the level approach of considering the characteristics and properties of individual micro- and nanocontacts of the friction zone, and then, by integrating or averaging over the surface, proceed to investigations at the meso- and macrolevels. This approach has become available only in recent years in connection with the development of nanoidentification and nanoscraping techniques.

Purpose

The aim of this work is to elucidate the physical nature of the processes occurring in the surface layers of the friction zone of mating parts of systems and aggregates of transport machines based on the data of their tribophysical essence and a set of chemical reactions occurring at the nano- and microlevel, representing the mechanisms of processes.

Results

An important step towards the creation of a physical theory of friction and wear of mating parts of systems and machine assemblies is the transition to research at the nanoscale. Such studies have become possible thanks to the improvement of scanning probe microscopes, in particular, atomic force microscopes operating in the lateral mode (friction for semicroscopy – FFM). On the basis of this information, various processes in the materials of dynamic tribocontacts have been modeled, new approaches to identifying regularities have been elucidated, and the mechanism of their development has been refined.

This indicates that the study of the processes of friction and wear in this direction goes to a higher quality level. At the same time, a whole series of new questions arise that need to be clarified, identified and resolved. The main ones are the issues of determining the characteristics and properties of the friction zone and the relationship between them on the macroscopic, mesoscopic, microscopic, nanoscopic. It needs an explanation and the result of their forecasting in the process of development and operation, as well as the identification of sets of processes that correspond to them. The state of triboconjugations in the surface layers of materials, which are formed in the process of self-organization, are also of interest and synergistic foundations of the "green" tribology of systems and machine assemblies are being created. When solving these issues, it is advisable to proceed from fundamental knowledge of the properties of interacting atoms and the topology of the working surfaces of mating parts.

It is also necessary to solve the issues of controlling external and internal friction in tribo-couplings of parts of systems and machine units on the basis of this knowledge. This will make it possible to create new and improved existing tribosystems (tribosystems of parts) with high friction and energy dissipation. For example, for tribo-couplings of parts of braking and friction systems, clutches or, conversely, for tribo couplings of parts with low friction (sliding bearings, for guide parts of systems and assemblies: valve bush, brake calipers, car suspensions, etc.).

In this case, it is desirable to identify conditions in which friction is practically zero, that is, the phenomenon of wear-free or positive selforganization is realized. There are no fundamental obstacles to this, and in a sense, such regimes have already been found.

Interaction in mobile interfaces of machine parts (fig. 1) is accompanied by a complex of different processes: mechanoemission, mechanochemical, gasdischarge, etc., as well as the course of tribochemical reactions, the synthesis of some compounds - the emergence of high-energy particle flows: excited molecules, atoms, ions, fast electrons, phonons (sound quanta), photons (quanta of electromagnetic radiation).

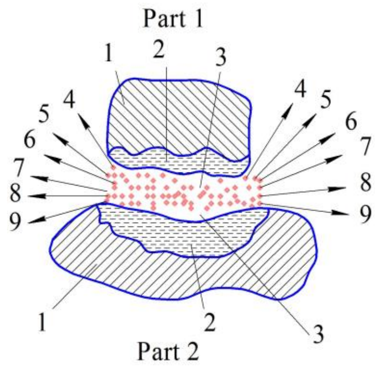

Fig. 1. Schematic representation of the triboplasma model in conjugation of details:
1 – the original structure of the material of the part; 2 – molten structure of the contact zone; 3 – plasma state of matter in the contact zone; 4 – triboemission electrons; 5 – flows of atoms, photons, phonons, ions, excited molecules, fast electrons; 6 - area of the reactor compartment of cold synthesis; 7 – heat flow; 8 – helium flow; 9 – fluxes of radiation of various types of energy; acoustic waves, triboluminescence, triboemission, exoelectron emission, photoelectron emission, photoelectric effect

The regularity of the additivity of the elastic aftereffect in the volumetric parts and surface layers of the parts of tribocouplings [20] has been revealed, which consists in the fact that in their elastic and plastic regions, in the zone of frictional contact, there is a summation (additivity) of elastic and plastic aftereffects caused by changes in frictional bonds, physical and mechanical characteristics of the material and the spatial position of the tribocouplings of parts. This is due to the directed movement of dislocations in the elastic and plastic regions of the surface layers of the material of the parts.

The regularity of the additivity of the magnetic aftereffect in the volumetric parts of the ferromagnetic material of the details of tribo-couplings and their surface layers has been also established [21]. The effect is that the summation (additivity) of magnetic aftereffects occurs in the elastic and plastic regions of the frictional contact zone. This aftereffect determines the behavior of hydrogen atoms in triboconjugation materials: intense diffusion is observed, a high degree of energy pumping in the surface layers, molization and interaction with atoms of other chemical elements dissolved in the main material of the parts. This is due to the directional movement of dislocations in the materials of parts, which capture hydrogen atoms and transport them to the zone of frictional contact with elastic and plastic local regions of the surface layers of materials of parts and affect their structure, as well as the mobility of the domain walls in them.

One of them is realized in tribocoupling of parts with helium wear [19]. The use of such tribosystems will make it possible to control friction due to superfluidity and the presence of helium parts in materials.

In this direction, a positive point is the established regularity of the additivity of the diffusion magnetic aftereffect in the volumetric parts and surface layers of tribocouplings of parts made of ferromagnetic materials and alloys [3]. Its essence lies in the fact that in the elastic and plastic regions of the material of the parts, in the zone of their frictional contact, the summation (additivity) of diffuse magnetic aftereffects occurs. In this case, the effect is accompanied by elastic and plastic aftereffects and determines the behavior, first of all, of the carbon and nitrogen atoms embedded in the material of parts. In the process of friction of the mates of parts, a directed movement of dislocations is observed, which transport the carbon and nitrogen atoms present in the materials of the parts into the zone of frictional contact with the elastic and plastic regions and their influence on the structure and mobility of the domain walls of the material.

It should be noted that the carbon C and nitrogen N atoms, which work by the interstitial mechanism, create the so-called carbon-nitrogen cycle, which is responsible for the synthesis of helium in the friction zone

[22]. The revealed conditions under which friction in the mating of parts is practically absent and the phenomenon of super-sliding is realized [7,23], similar to the phenomena of superconductivity or superfluidity.

A tribophysical model of such a selforganization phenomenon can be built on the basis of the carbon-nitrogen cycle of a number of the following chemical reactions:

$$^{12}C+^{1}H\rightarrow^{13}N+\gamma; \quad (1)$$
$$^{13}N\rightarrow^{13}C+\beta^{+}+\nu; \quad (2)$$
$$^{13}C+^{1}H\rightarrow^{14}N+\gamma; \quad (3)$$
$$^{14}N+^{1}H\rightarrow^{15}O\rightarrow+\gamma; \quad (4)$$
$$^{15}O\rightarrow^{15}N+\beta^{+}+\nu; \quad (5)$$
$$^{15}N+^{1}H\rightarrow^{12}C+^{4}He. \quad (6)$$

In these tribochemical reactions, the carbon atom plays the role of a catalyst for the process of proton fusion. A proton, colliding with a carbon nucleus ^{12}C (1), turns into a radioactive isotope ^{13}N, and a γ-quantum (photon) is also emitted. The ^{13}N isotope, undergoing β^{+} decay with the emission of a positron and neutrino (2), turns into an ordinary nitrogen nucleus ^{14}N (3). In this reaction, a γ-quantum is also emitted. Further, the ^{14}N nitrogen nucleus collides with the ^{1}H (4) proton, after which a radioactive oxygen isotope ^{15}O and a γ-quantum are formed. Then this isotope is converted by β^{+} decay into the nitrogen isotope ^{15}N (5). Finally, the last ^{15}N isotope, having attached a proton during the collision, decays into ordinary carbon ^{12}C and helium ^{4}He (6).

The entire chain of nuclear reactions observed are the sequential weighting of the carbon nucleus by the addition of protons, followed by β^{+} decay. The last link in this chain is the restoration of the original carbon nucleus and the formation of a new helium nucleus at the expense of four protons, which at different times, one after another, joined to ^{12}C and to the isotopes that were formed from it.

In recent years, numerous experimental realizations of details of local nuclear reactions at low energies, that is, realizations of local nuclear reactions in condensed media, have been obtained in tribological conjugation materials. This is the so-called cold nuclear fusion (CNF). On the basis of CNF, it is proposed to replace the nuclear processes induced by the crystal lattice of the material. These processes are anomalous in terms of vacuum nuclear collisions. First of all, this fusion of nuclei with the release of neutrons that exist in non-equilibrium solid materials of parts during friction is stimulated by the transformation of elastic energy in the crystal lattice during phase transitions, mechanical influences, sorption or desorption of hydrogen (deuterium). CNF has been reliably recorded in a number of physical and physicochemical processes involving deuterium. Many of them with the participation of natural hydrogen take place in natural processes. These include: the phenomenon of sorption-desorption of hydrogen in metals, redox effect on the compound of hydrogen, mechanical damage and crushing of hydrogen containing rocks.

Note that a satisfactory quantitative and even qualitative theory of CNF has not been created yet, which is of fundamental importance both for fundamental science and for practical use. At the same time, original theoretical and physical models of the CNF mechanism in the crystal structures of the surface layers of tribointerface parts made of ferromagnetic materials and alloys have been developed. An unknown regularity of the additivity of the hydrogen magnetic aftereffect in the bulk parts and surface layers of these materials has been established [22]. It consists in the fact that in elastic and plastic regions, in the zone of their frictional contact, there is a summation (additivity) of hydrogen magnetic aftereffects. Accompaniment by elastic and plastic aftereffects cause directional displacement of dislocations carrying hydrogen to the contact zone. As a result, a number of chemical reactions occur in the tribocontact zone:

$$^{1}H+^{1}H\rightarrow^{2}D+\beta^{+}+\nu; \quad (7)$$
$$^{2}D+^{1}H\rightarrow^{3}He+\gamma; \quad (8)$$
$$^{3}He+^{3}He\rightarrow^{4}He+2^{1}H. \quad (9)$$

On the basis of this, it is possible to formulate the CNF mechanism, which arises in the surface layers of triboconjugation parts, which determines the directional dislocation movement in the crystal structures of the surface layers of materials with the implementation of the proton cycle. As a result, hydrogen is converted to helium.

It should be noted that academician B.V. Deryagin and his co-workers in 1985 discovered the phenomenon of neutron mechanoemission in crystalline materials containing deuterium. In his publications, he interpreted this phenomenon as a manifestation of CNF reactions. It was hypothesized that in substances with hydrogen bonds, one of the bonds may contain two nuclei of hydrogen atoms with a distance between them less than one angstrom. It was found that tunneling of deuterons through a narrow barrier can occur with a high probability even at relatively low temperatures.

Note that according to modern concepts of nuclear physics, a proton and a neutron have two states of one particle – a nucleon. A proton becomes a neutron, attaching an electron, and a neutron - a proton, giving an electron to another proton, which, in turn, turns into a neutron.

On the basis of what has been considered, the idea of the known mechanocaloric effect [7, 8] is changing and it is possible to substantiate a number of effects and processes that arise in materials in the friction zone from a purely physical position of nanotribology. This can be used to create competitive technologies in the field of hydrogen energy, cryogenic and space technology. By taking into account an additional trend in the output parameters due to the additivity of the elastic magnetic and hydrogen-magnetic aftereffect in the volumetric parts and surface layers of the materials of the parts of tribocouplings of systems and machine units, it is possible to control the processes of friction and wear in them.

Conclusions

1. Considering that the contact zones of the materials of parts interacting in microelectromechanical and nanoelectromechanical systems, such as miniature telework, microsatellites, microdevices, nanocomputers, microsensor devices, chemical and biochemical microreactors, and others, are very small, and the specific loads on nanocontacts are large, then tribological processes are largely determined by the atomic-molecular interaction of contacting surfaces and are manifested primarily at the nano- and micro-level of the hierarchy of the totality of tribological processes.

2. It is urgent to create materials for mating parts with helium wear with the possibility of quenching it based on the implementation of a carbon-nitrogen cycle (effect) in the friction zone, as well as ensuring friction control due to the superfluidity of helium in micro- and nanotribosystems.

3. Creation of nanotechnologies and a new class of devices for microelectromechanical and nanoelectromechanical systems will give new competitive results, in particular, through the creation and use of tribosystems with helium wear, which will provide updated diagnostic information about the local states of materials and the identification of new processes in the friction zone.

4. The study of nuclear processes induced by the crystal lattice in micro- and nanotribology is of interest both from the point of view of fundamental research on the creation of a generalized theory of friction and wear, the creation of effective tribotechnologies of running-in and recovery, and for applied purposes.

5. The use of hydrogen as a fuel in a car engine, as well as the development of hydrogen energy can actualize the creation of materials for triboconjugation of parts with helium wear with the possibility of its extinguishing based on the implementation of a carbon-nitrogen cycle (effect) in the friction zone, as a result of which hydrogen is converted into helium.

6. The essence of the acoustic wave, tribological effects, triboelectronic, photoelectronic and triboemissions arising from the interaction of nanocontacts in tribosystems can be purposefully used not only in the study of cold nuclear fusion, but also for obtaining in the future an inexhaustible source of ecologically clean energy based on the synthesis of helium from more light hydrogen.

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Аулін В.В., Лисенко С.В., Гриньків А.В., А.Є. Чернай, І.В. Жилова Новий підхід до з'ясування фізичної природи процесів, що відбуваються в зоні тертя спряжень деталей машин

З'ясовано, що при фрикційному контакті в окремих локальних ділянках тонкого поверхневого шару деталей при значних напруженнях і деформаціях та високих контактних температур матеріал зони трибоконтакту деталей переходить в особливий активізуючий нестійкий стан магми-плазми або трибоплазми. Загальні питання, в яких з'ясовується природа процесів тертя та зношування спряжень деталей, розглянуто на більш високому фундаментальному рівні із залученням нанотрибології.

Проаналізовано ряд процесів, якими супроводжуються взаємодії трибоспряжень деталей.: механоемісійні, механохімічні, газорозрядні та ін., трибохімічні реакції, потоки частинок з великою енергією: збуджених молекул, атомів, іонів, швидких електронів, фононів (звукових квантів та квантів електромагнітного випромінювання).

Виявлено закономірності адитивності пружної та магнітної післядій в об'ємних частинах і поверхневих шарах деталей трибоспряжень з феромагнітних матеріалів і сплавів. Також встановлена закономірність адитивності дифузійної післядії в їх поверхневих шарах. Побудовано трибофізичну модель самоорганізації на основі вуглецево-азотного циклу реалізацій трибохімічних реакцій, які мають зміст термоядерних реакцій синтезу і які можливо розглядати на нанорівні. В цих реакціях атом вуглецю відіграє роль каталізатора процесу злиття протонів з подальшим перетворенням в радіоактивний ізотоп, який розпадається на звичайний вуглець і гелій. З'ясовано, що механізм реакцій ядерного синтезу в поверхневих шарах деталей трибоспряжень, обумовлений спрямованим переміщенням дислокацій в кристалічних структурах матеріалів з реалізацією протонного циклу та перетворенням водню в гелій.

Показано, що зазначене дає можливість змінити уявлення про механокалоричний ефект, процес тертя і зношування та обґрунтувати ряд ефектів і процесів з фізичних позицій нанотрибології. Це дасть можливість створити конкурентоспроможні триботехнології в різних галузях.

Ключові слова: спряження деталей, критерії тертя, зносостійкість, надійність систем і агрегатів.

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Assessment of the quality factor of tribosystems and relationship with tribological characteristics

V.A. Vojtov, A.V. Voitov

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

Abstract

The definition of the quality factor of the tribosystem has been further developed, which, unlike the known one, takes into account not only the geometric dimensions of the tribosystem, thermal diffusivity of triboelement materials, lubricating medium and deformation propagation rate in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in. Theoretical studies have established that three parameters have the maximum effect on the quality factor: sliding speed, roughness of friction surfaces and lubricating medium.

Experimental studies have established the relationship between the value of the quality factor, wear rate and coefficient of friction during steady-state operation of tribosystems. It has been shown that an increase in the figure of quality factor reduces the above parameters, and the criterion itself Q_{max} is a measure of the potential of the tribosystem adapt to the operating conditions.

Keywords: tribosystem, modeling, wear rate, coefficient of friction, material compatibility, quality factor of tribosystem, the criterion quality factor of tribosystem, internal friction of material structure

Introduction

The concept of the quality factor of a tribosystem was introduced by the authors of the work [1] and is defined as the ability of mating materials in the 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 greater part of the friction work will be converted into heat and less material will be involved in deformation, then there is a greater quality factor of the tribosystem.

The concept of the quality factor of a tribosystem complements the concept of material compatibility in a tribosystem, which is understood as the ability of contacting materials to adapt to each other and to changing friction conditions, taking into account the interaction of materials with the lubricant and the environment, ensuring the specified durability and stable operation over the entire range of operation.

As follows from the above definition, the quality factor of the tribosystem is influenced by the processes of formation of surface layers during friction, tribological properties of the lubricating medium, as well as the design of the tribosystem, rheological properties of the structure of conjugated materials and the nature of the applied load to the tribosystem.

For predicting the wear resistance of tribosystems, as well as for calculating the wear rate and friction losses, it is necessary to have a quantitative parameter for assessing the quality factor of the tribosystem, which is a multi-parameter function of processes, flowing in the surface and subsurface layers of materials and depends on the nature of the applied load.

Literature review

The problem of material compatibility in the tribosystem belongs to the works [2-4] which define the concept of material compatibility, which consists in the ability of contacting materials to adapt to each other and to changing friction conditions, taking into account the interaction of materials with the lubricant and the environment, ensuring the specified durability of the tribosystem and its stable operation without lubrication or in the mode of violation of the integrity of the lubricant. In later work [5], the concept of compatibility was clarified - as the ability of a tribosystem to provide an optimal state in a given range of operating conditions for the selected parameters.

Considering that friction is a dynamic and dissipative process, internal friction can serve as a quantitative characteristic of the relaxation properties of the surface layers of materials [6, 7]. Internal friction characterizes the ability of a material structure to dissipate vibration energy, related to the density, concentration and mobility of dislocations and point defects.

In works [8-10], it is shown that relaxation processes exhibit a higher structural sensitivity to changes in the stress-strain state of the material under dynamic loading compared with physical and mechanical properties. The main conclusion of the above works is that the rheological properties of the frictional contact can be represented in the form of four levels, in which the processes of contact interaction are concentrated.

Based on the performed analysis of the work we can conclude, that the relaxation properties of the structure of the materials from which the tribosystem is made affect the compatibility of materials, and are a function of wear resistance and running-in, which is proven in work [11]. In this work, a parameter is given - the attenuation coefficient of ultrasonic vibrations in the structure of the material, which characterizes the amount of internal friction and the method of its measurement.

Analyzing the presented material, we can conclude, that the development of a criterion that would more fully take into account the above factors is an urgent task.

Purpose

The aim of this work is to develop a criterion for assessing the quality factor of a tribosystem and assess its functional relationship with the wear rate, friction coefficient and running-in time.

Methods

According to work [1] the quality factor of the tribosystem can be estimated by the expression:

$$Q = \frac{K_f^2 \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot \sqrt{\frac{\delta_{mov} \cdot \delta_{fix}}{\pi}}, J/m^3. \quad (1)$$

A parameter that takes into account the geometric dimensions of the tribosystem, the form factor Кf, according to work [12] is calculated by the formula:

$$K_f = \frac{F_{\min}}{V_{mov} + \frac{V_{fix} \cdot F_{\max}}{F_{\min}}}, \frac{1}{m}, \quad (2)$$

where F_{min} – friction area of a fixed triboelement, m^2;
V_{mov} – volume of material under the friction area of a movable triboelement, m^3;
V_{fix} – volume of material under the frictional area of a fixed triboelement, m^3;
F_{max} – friction area of the movable triboelement, m^2.

Significant parameters are also: thermal diffusivity of materials of triboelements a, m^2/s and the strain rate in these materials $\acute{\varepsilon}$, 1/s on actual contact spots. Considering that a movable and a fixed triboelement simultaneously participate in the tribosystem, we use the concepts of reduced values.

The reduced coefficient of thermal diffusivity of the tribosystem materials is determined by the expression:

$$a_{red} = \frac{2 \cdot a_{mov} \cdot a_{fix}}{a_{mov} + a_{fix}}, m^2/s, \quad (3)$$

where a_{mov} and a_{fix} – thermal diffusivity coefficients of materials of movable and fixed triboelements, reference value, m^2/s.

Tribological properties of the lubricating medium, according to work [13], can be taken into account using the parameter E_u, J/m^3 – specific work of wear per unit volume of test material (balls of steel ShH-15) in the tested lubricating medium. Formula for calculating values E_u based on the results of an experiment on a four-ball machine, is presented in work [13].

The reduced strain rate in the surface layers of the tribosystem materials is determined by the expression:

$$\dot{\varepsilon}_{red} = \frac{2 \cdot \dot{\varepsilon}_{mov} \cdot \dot{\varepsilon}_{fix}}{\dot{\varepsilon}_{mov} + \dot{\varepsilon}_{fix}}, 1/s, \tag{4}$$

where $\dot{\varepsilon}_{mov}$, $\dot{\varepsilon}_{fix}$ – deformation rate of materials of moving and fixed triboelements, 1/s. Based on work [14]:

$$\dot{\varepsilon}_{mov} = 75(1+\mu_{mov})(0{,}86 - 1{,}05\mu_{mov}) \frac{\sigma_{acp} \cdot v_{sl}}{E_{mov} \cdot d_{acp}}, \text{ 1/s}, \tag{5}$$

$$\dot{\varepsilon}_{fix} = 75(1+\mu_{fix})(0{,}86 - 1{,}05\mu_{fix}) \frac{\sigma_{acp} \cdot v_{sl}}{E_{fix} \cdot d_{acp}}, \text{ 1/s}, \tag{6}$$

where μ_{mov} and μ_{fix} – Poisson's ratios of materials of movable and fixed triboelements, reference value;
σ_{acp} – stress at the actual contact patch, calculated by the formula presented in the work [14], Pa;
v_{sl} – sliding speed, m/s;
E_{mov} and E_{fix} modulus of elasticity of materials of moving and fixed triboelements, reference value, Pa;
d_{acp} – diameter of the actual contact patch, m^2, calculated by the formula presented in the work [14], Pa.

The structure of conjugated materials in the tribosystem, according to the formula (1), is taken into account by values δ_{mov} and δ_{fix} – damping coefficients of ultrasonic vibrations in the structure of the material of the moving and stationary triboelements, dimensionless and constant values. These coefficients are directly proportional to the internal friction of the original structure of conjugated materials and do not change during running-in.

However, according to the conclusions of the work [15], the rheological properties of the structure of conjugated materials are not constant, but change (increase) during the running-in time for 30,7…33,9%. When studying transient processes in tribosystems and substantiating effective programs for their running-in [16], it is necessary to take into account the function of changing the rheological properties of tribosystem materials in time - $RS_{TS}(t_i)$.

To assess the rheological properties of the structure of conjugated materials in the tribosystem during running-in, when t_i varies from zero to t_r, let's use the expression:

$$RS_{TS}(t_i) = \sqrt{\frac{\delta_{mov}(t_i) \cdot \delta_{fix}(t_i)}{\pi}}, 1/m, \tag{7}$$

where $RS_{TS}(t_i)$ - values of rheological properties of connected materials in the tribosystem, as a function of running time, dimension 1/m;

$\delta_{mov}(t_i)$ - the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the movable triboelement, as a function of the running time, the dimension dB/m, is calculated by the expression given in the work [15];

$\delta_{fix}(t_i)$ – the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the fixed triboelement, as a function of the running time, the dimension dB/m, is calculated by the expression given in the work [15].

The basis of the methodological approach when supplementing the criterion of quality factor of the tribosystem instead of constant values that take into account the initial structure of materials in the tribosystem is the formula (1), we use the function of changing the rheological properties of tribosystem materials in time - $RS_{TS}(t_i)$. Using the analysis of the dimensions of physical quantities, we write expressions for determining the quality factor during the transient process:

$$Q(t_i) = \frac{K_f \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot RS_{TS}(t_i), J/m^3, \tag{8}$$

and after the end of the transition process:

$$Q_{\max} = \frac{K_f \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot RS_{TS(\max)}, J/m^3. \tag{9}$$

The given expressions for evaluating the quality factor of the tribosystem during running-in, the formula (8) and after the completion of the running-in (at steady state), the formula (9), unlike the well-known (1), take into account not only the geometric dimensions of the tribosystem, the thermal diffusivity of the materials of the triboelements, lubricating medium and the rate of propagation of deformation in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in.

The listed differences will improve the accuracy of modeling the wear rate and coefficient of friction during transient processes and at steady-state modes of tribosystem operation.

Results

As follows from the above expressions (8) and (9) the quality factor of the tribosystem is a quantitative parameter that characterizes the design of the tribosystem - the parameter K_f, thermal diffusivity of triboelement materials a_{red}, tribological properties of the lubricating medium E_u, strain rate in the surface layers of triboelements ($\dot{\varepsilon}_{mov}$, $\dot{\varepsilon}_{fix}$), which depends on the roughness of the friction surfaces and the elastic modulus of the materials of the triboelements (E_{mov} and E_{fix}), as well as the function of changing the rheological properties of the surface layers of materials during running-in $RS_{TS}(t_i)$ and their increase during the running-in time $RS_{TS(max)}$.

Dependences of the change in the value of the figure of merit on the change in the coefficient of the form of the tribosystem K_f, rheological properties of the structure of conjugated materials $RS_{TS(max)}$ their thermal diffusivity a_{red} and tribological properties of the lubricating medium E_u, are shown in fig. 1. These are parameters, an increase in which directly affects the figure of the quality factor, with the exception of the tribological properties of the lubricating medium. E_u and the reduced coefficient of thermal conductivity of the materials of triboelements.

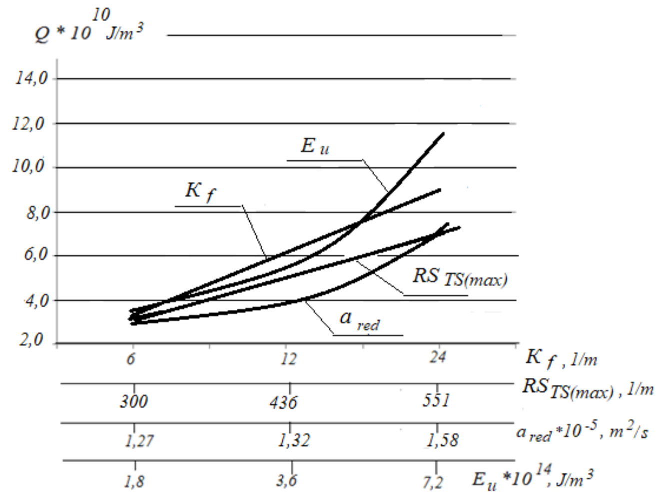

Fig. 1. Dependences of the change in the figure of the quality factor of tribosystems on the change in the shape factor, the rheological properties of the materials of the triboelements, their thermal diffusivity and the tribological properties of the lubricating medium

As follows from the analysis of the curves, the greatest influence on the figure of the quality factor is exerted by the tribological properties of the lubricating medium E_u, further, in decreasing order, the form factor, which characterizes the structure of the tribosystem, rheological properties of the structure of materials and thermal diffusivity of materials of triboelements.

The value of the reduced strain rate in the surface layers of materials of triboelements $\dot{\varepsilon}_{red}$, formula (4), is inversely proportional to the figure of the quality factor, the formula (8), (9). The parameters that are included in the expressions for the deformation rate of the materials of the fixed and movable triboelements are determined by the expressions (5) and (6), the influence of which is shown in fig. 2.

The analysis of the obtained dependences allows us to conclude that the greatest influence on the quality factor of the tribosystem is exerted by the value of the sliding speed, and then, in decreasing order, the roughness of the friction surfaces and the load.

The conducted theoretical studies allow us to evaluate the influence of the above parameters on the quality factor of tribosystems. At the same time, the range of parameter variation is selected within the limits of tribosystem functioning in normal wear modes, i.e. without damage. The ratio of the maximum value of the figure of the quality factor to the minimum value, when one of the parameters changes, makes it possible to determine how many times the figure of the quality factor indicator changes within the given modeling limits.

Two parameters have the maximum influence on the quality factor: sliding speed and surface roughness. In this case, sliding speed comes first – 11,2 times, and the surface roughness is the second – 6,5 times.

In the third place is the tribological properties of the lubricating medium - 4,7 times, the form factor – 3,0 times, rheological properties of materials and thermal diffusivity of materials of triboelements – 2,55 times.

Based on the performed rating, it is possible to justify the parameters that affect the quality factor, and consequently, the tribological properties of tribosystems. These are the sliding speed, the roughness of the friction surfaces and the lubricating medium.

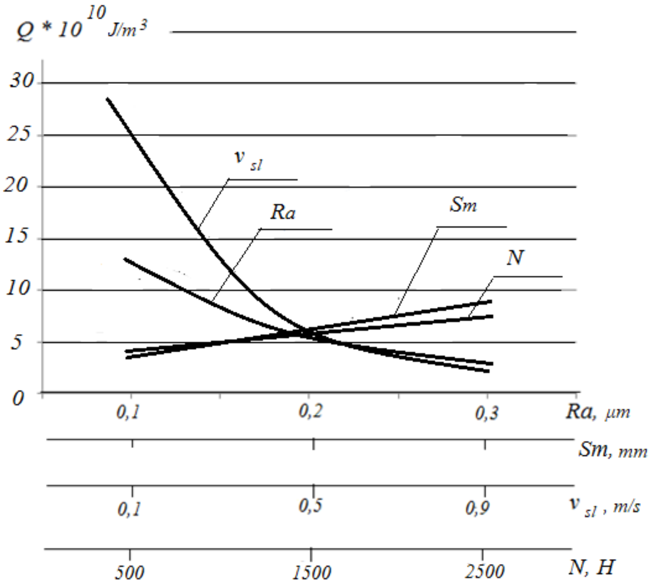

Fig. 2. Dependences of the change in the value of the figure of the quality factor of tribosystems on the change in the roughness of the friction surfaces, load and sliding speed

The form factor of the tribosystem does not change during the running-in process. This is a value that is determined during design and is a constant during the running-in and operation of the tribosystem.

The value of roughness is also formed in the process of manufacturing tribosystems, however, in the process of running-in and operation, it changes and comes to an equilibrium value. The tribological properties of the lubricating medium also do not change during the running-in process, however, they change during operation. Based on the foregoing, we can conclude that the running-in process can be controlled by changing $\dot{\varepsilon}_{red}$, formulas (5) and (6), in the direction of decreasing. To do this, it is necessary to reduce the sliding speed υ_{sl} and load *N*. Analysis of the dependencies shown in fig.2 allows us to state that the change in load *N* insignificantly affects the figure of the quality factor, and the sliding speed υ_{sl}, is an effective parameter, changing which you can control the running-in process.

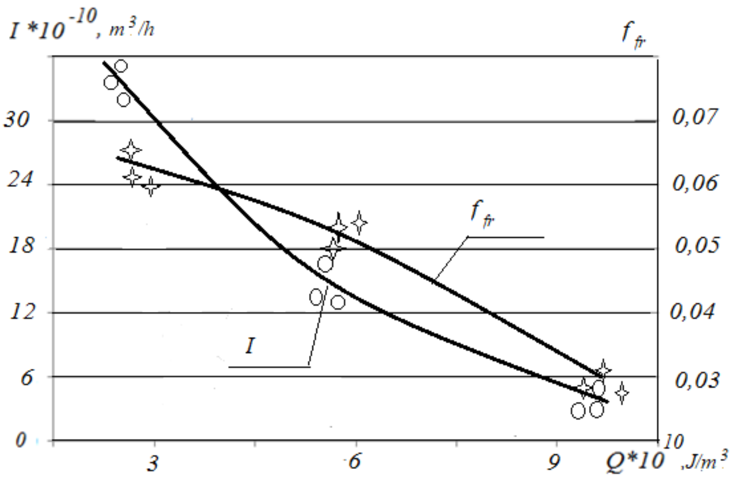

Fig. 3. Dependence of the change in the volumetric wear rate and the coefficient of friction in the steady-state mode of operation on the value of the quality factor of the tribosystems

In the fig.3 experimental values and curve fitting (solid lines) changes in volumetric wear rate *I* and coefficient of friction f_{fr} in the steady-state operating mode of tribosystems with different quality factors are presented. Analysis of the obtained dependences allows us to conclude that an increase in the quality factor of the tribosystem by 4 times reduces the rate of volumetric wear by 9 times and the coefficient of friction by 2,4 times.

The obtained experimental results allow us to conclude that there is a functional relationship between the volumetric wear rate, friction loss and the quality factor of tribosystems. The presented experimental studies allow us to conclude that the quality factor of tribosystems Q_{max} can act as a measure of the potential of the tribosystem adapt to the operating conditions providing the maximum resource.

Conclusions

1. The definition of the quality factor of a tribosystem was further developed, which, unlike the known one, takes into account not only the geometric dimensions of the tribosystem, thermal diffusivity of triboelement materials, lubricant medium and the rate of propagation of deformation in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in. Theoretical studies have established that three parameters have the maximum effect on the quality factor: sliding speed, roughness of friction surfaces and lubricating medium.

2. Experimental studies have established the relationship between the value of the figure of the quality factor, wear rate and coefficient of friction during steady-state operation of tribosystems. It is shown that an increase in the figure of the quality factor reduces the above parameters, and the criterion itself Q_{max} is a measure of the potential of the tribosystem adapt to the operating conditions.

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Войтов В.А., Войтов А.В. Оцінка добротності трибосистем і її зв'язок з трибологічними характеристиками

Отримало подальший розвиток визначення добротності трибосистеми, як здатність сполучених матеріалів в трибосистемі (мастильне середовище та реологічні властивості структури матеріалів рухомого і нерухомого трибоелементів), перетворювати роботу сил тертя в теплову енергію, тим самим перешкоджати запасам енергії в поверхневих і підповерхневих шарах трибоелементів, які можна оцінити об’ємом що деформується. Представлено вираз для розрахунку кількісної величини добротності, який на відміну від відомих враховує не тільки геометричні розміри трибосистеми, температуропровідність матеріалів трибоелементів, мастильне середовище і швидкість поширення деформації в поверхневих шарах матеріалу, а також функцію зміни реологічних властивостей поверхневих шарів під час припрацювання і їх збільшення за період припрацювання. Теоретичними дослідженнями встановлено, що максимальний вплив на добротність надають три параметри: швидкість ковзання, шорсткість поверхонь тертя і мастильне середовище.

Представлені експериментальні значення зміни об'ємної швидкості зношування і коефіцієнта тертя на сталому режимі роботи трибосистем з різною добротністю. Аналіз отриманих залежностей підтверджує, що збільшення добротності трибосистеми в 4 рази знижує величини швидкості об'ємного зношування в 9 разів і коефіцієнта тертя в 2,4 рази. Отримані результати дозволяють стверджувати, що збільшення добротності покращує трибологічні характеристики трибосистем, а сам критерій Q_{max} є мірою потенційної можливості трибосистеми пристосовуватися (адаптуватися) до умов експлуатації.

Отримані теоретичні та експериментальні результати доводять про наявність функціонального зв'язку між об'ємною швидкістю зношування, втратами на тертя і величиною добротності трибосистем.

Ключові слова: трибосистема, моделювання, швидкість зношування, коефіцієнт тертя, сумісність матеріалів, добротність трибосистеми, критерій добротності трибосистеми, внутрішнє тертя структури матеріалів

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Influence of carbon fiber on tribotechnical characteristics of polyetheretherketone

O.I. Buria, A.-M.V. Tomina[1], I.I Nachovnyi [2]

[1]Dniprovsk State Technical University, Ukraine
[2] Ukrainian State University of Chemical Technology, Ukraine
E-mail: an.mtomina@gmail.com

Abstract

Superstructural thermoplastic polymers, including polyetheretherketone, are now widely used in many industries. However, its rather high coefficient of friction and insufficient wear resistance limits its use in friction units of machines and mechanisms. This article covers the influence of T700 Toray carbon fiber on the tribotechnical characteristics of Victrex150G aromatic polyetheretherketone. As a result of the researches it has been found out that the developed carbon plastics exceed the base polymer in friction coefficient and wear 1.2-1.54 and 1.7-8.8 times, respectively, due to the formation of a stable "transfer film" on the steel counterbody (so-called antifriction layer): finely dispersed particles of the polymer matrix and crushed products of wear of carbon fiber penetrate into the microcavities of the counterbody. This is confirmed by the fact that the roughness of carbon plastics has decreased by 50 % in cpomparison with the base polymer. The greatest improvement in tribological properties is observed at 10 mass%, of carbon fiber content, then the properties get worse. That can be explained by the increase in defects of the material due to the dominant loosening at the "polymer-fiber" boundary that confirms the results of microhardness and ultrasonic control. The obtained results show that the composite with an effective carbon fiber content (10 mass%) can be recommended for the manufacture of parts of movable joints of machines and mechanisms operating under friction without lubrication in various industries: agricultural, automotive and textile. etc.

Key words: aromatic polyetheretherketone, carbon fiber, wear, friction coefficient, ultrasonic control, microhardness, friction units

Introduction

One of the important factors limiting the trouble-free and stable operation of agricultural, aviation and automotive equipment is the wear (up to 6 mm) of the contact surfaces of the sliding friction units [1] that are equipped with metal parts. The use of polymer composite materials (PCM) based on thermoplastic polymer matrices allows to solve this problem and get a number of advantages. Thus, plain bearings made of PCM are characterized by high mechanical and tribotechnical characteristics combined with low weight, chemical and thermal resistance. In addition, a wide variety of polymer composites, which differ in their technical indicators, allows to select an effective material for specific operating conditions. Another important advantage of PCM is the ability to develop new and improve (in order to get strong adhesive bonds that largely determine the technical characteristics of polymer composites) that allows to expand their use and increase their competitiveness with other traditional materials [2].

Literature review

Carbon fiber (CF) is now one of the most common fillers for the creation of PCM based on thermoplastic binders - carbon plastics (CP) for tribotechnical and structural purposes [3]. Thus, the use of CF as a filler allows to obtain composites with high specific strength, high environmental friendliness, the ability to work in heavily loaded friction units without lubrication [4], low density and almost zero coefficient of thermal linear expansion (CTLE), lightness that allow them to compete with known serial materials (bronze, titanium, babbitt, cast iron, etc.). CF have been widely used to fill polyetheretherketone (PEEK). However, there are disadvantages that hinder the widespread implementation of these CP: anisotropy of characteristics due to the uneven distribution of CF in the polymer matrix, insufficient high operating temperature, high cost of manufacturing products [5]. Taking into account the above, the search for new carbon fiber based on PEEK with high performance indicators is an urgent task.

Methods

Victrex150G polyetheretherketone (manufactured by ICI) was chosen as the polymer matrix. PEEK is characterized by a unique set of performance characteristics: heat and fire resistance, resistance to many aggressive environments (acetone, trichlorethylene, ethyl acetate, gasoline, etc.), high-energy rays (even ultraviolet rays lead only to slight yellowing of the material) and radiation, low water absorption, high temperature of long (from 233 to 533 K) and short-term operation (up to 623 K). However, polyetheretherketone has high enough coefficient of friction (f> 0.4) and insufficient wear resistance that limits its use in the friction units of machines and mechanisms [6]. Among other plastics, PEEK has the lowest level of emissions of harmful gaseous substances under the influence of an open flame.

Toray T700 carbon fiber was selected as a filler (table 1).

Table 1

The main properties of Toray T700 carbon fiber

Indicator	Value
Density, kg / m3	1700 – 1800
Compressive strength, MPa	230
Modulus of elasticity, GPa	4900
Number of filaments	12000

Compositions containing 5-20 mass% of discrete carbon fiber were prepared by mixing the components in a rotating electromagnetic field in the presence of ferromagnetic particles. Processing of the mixture prepared by this method into block products was carried out by compression pressing at a pressure of 50 MPa and an effective pressing temperature of 628 K, hold time without pressure was 10 min., hold time under pressure was 5 min [7].

The study of tribotechnical characteristics of the base polymer and carbon plastics based on it was carried out in the mode of friction without lubrication on machine with reciprocating motion at a load of 0.637 MPa, a sliding speed of 1.03 m / s. The experiment time was 30 minutes. The samples were made of cylindrical shape Ø = 10, h = 15 mm,38H2MYUA steel was used as a counterbody (45-48 HRC, Ra = 0.16-0.32 μm). The obtained results were processed using the methods of mathematical statistics.

The depth of abrasion tracks (surface roughness, Ra, μm) of the original polymer and carbon plastics based on it was determined using a 170621profilometer using a sharp and hard needle (probe) that moved along the test surface copying its irregularities. The study of the morphology of the friction surfaces of unfilled polyetheretherketone and carbon plastics based on it was carried out using NEOPHOT-32optical microscope. In the study of microhardness the characteristics of reinforced plastics were obtained in its microvolumes at the "binder - fiber" boundary on the PMT-3M microhardness tester.

Non-destructive quality control (that allows to determine the presence of cracks and pores in the volumes of the composite) of the original polymer and composites based on it was determined by echo-pulse method using a universal ultrasonic UD2V-P46 flaw detector ("KROPUS", LLC "NPP Ukrintech"), in the mode of the automatic signaling of defect (ASD), frequency was 5 MHz, the period was 2,5, PEC was 5 MHz. This device is widely used to identify defects in materials due to its simplicity and high performance, reliability and versatility.

Results

Analysis of the results of tribological studies under friction without lubrication showed that the use of Toray T700 carbon fiber can reduce the coefficient of friction and wear of aromatic polyetheretherketone 1,2-1,54 (Fig. 1) and 1,7-8,8 (Fig. 2) times respectively. These results can be explained as follows. Carbon plastics are characterized by 1.3-1.7 times higher thermal conductivity than PEEK (studied by the authors in the work [8] that according to the fatigue theory of wear it prevents the localization of heat in the friction zone and thermomechanical destruction of polymers).

On the other hand, in the process of friction of carbon plastics (Fig. 3) there is a process of selective transfer [9]: finely dispersed wear products formed during friction fill the microcavities of the steel counterbody resulting in friction on the "transfer film" that acts as a dry lubricant and is characterized by low shear strength and high load capacity. There is a transition from the adhesive-fatigue mechanism of wear to pseudoelastic.

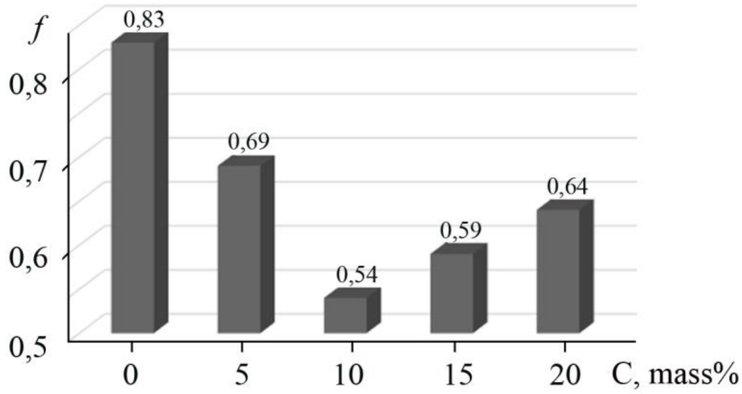


Fig. 1. Influence of carbon fiber on the friction coefficient of polyetheretherketone

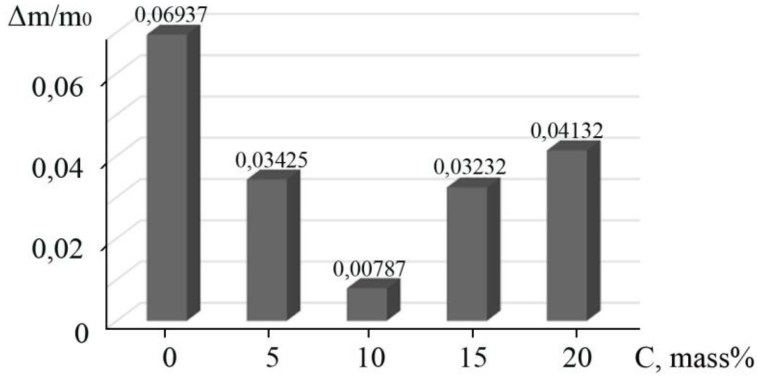
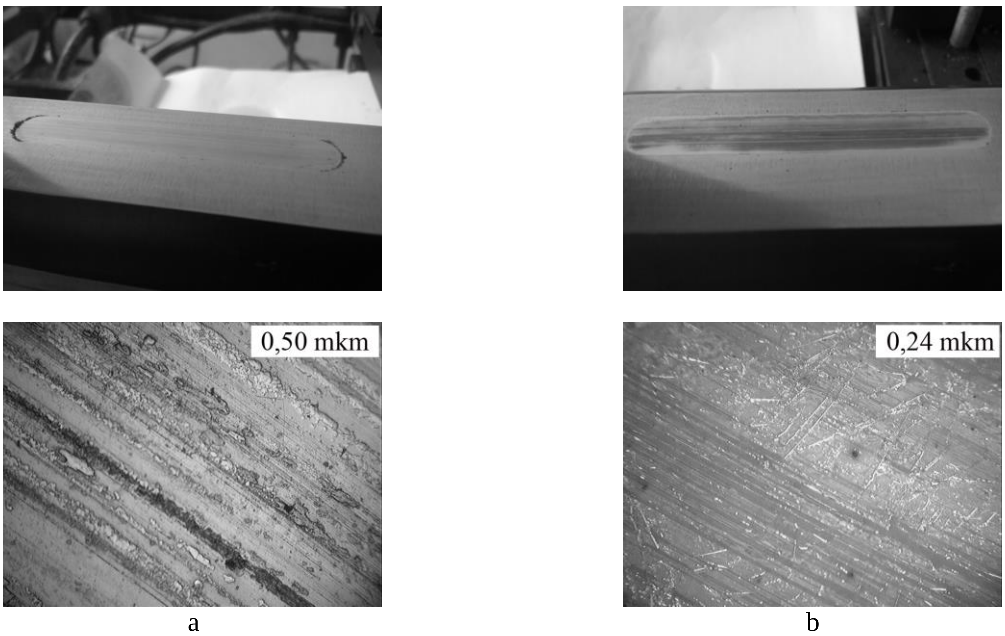


Fig. 2. Influence of carbon fiber on the wear of polyetheretherketone

This is confirmed by the study of the morphology of the friction surfaces of PEEK and carbon plastics based on it. It has been found out that with the introduction of 10 mass% of CF there is a significant smoothing of the microrelief of the carbon fiber surface. The average surface roughness of the initial polymer during carbon fiber reinforcement decreased by 2 times (Fig. 3). That is one of the important contributions to the overall improvement of tribological properties, because when the roughness decreases, the specific load in the contact areas decreases [10].



a b

Fig. 3. The surface of the counterbody and the sample after friction of polyetheretherketone (a) and carbon fiber (b) based on it containing 10 mass% of carbon fiber

On the other hand, the increase in the wear resistance of CP is due to the ability of materials to dissipate energy by reducing internal friction as a result of changes in the structure of the polymer binder (it becomes more ordered) that leads to a decrease in temperature of surface layers. As a result, adhesion zones are almost not observed on the friction surface of the polymer composite, in contrast to non-reinforced polyetheretherketone (Fig. 3).

The most intensive improvement of the tribotechnical characteristics of the initial polymer occurs with the introduction of CF up to 10 mass%. After that it begins to decrease. This is due to the increase in the defect of the material.

The appearance of defects (pores, cracks) in the volume of the material is due to poor impregnation of the polymer matrix of carbon fiber that are formed due to excessive amounts of the latter. This is confirmed by the study of microhardness at the " polyetheretherketone-fiber" boundary (Fig. 4). Thus, when the filler content is 15-20 mass%, the value of microhardness decreases by 10%. This indicates that at a fiber content of 5-10 mass% the ordering process of the binder prevails over loosening, and vice versa in the case of 15-20 mass%.

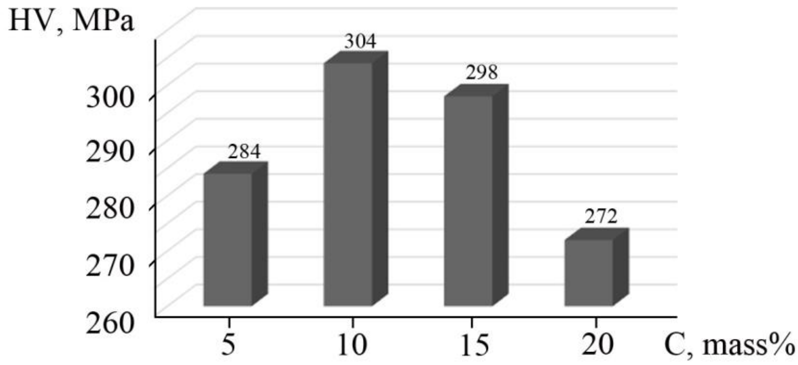


Fig. 4. Microhardness of carbon fiber at the "polymer-fiber" boundary

Another confirmation of this conclusion may be the data of ultrasound monitoring (Fig. 5).

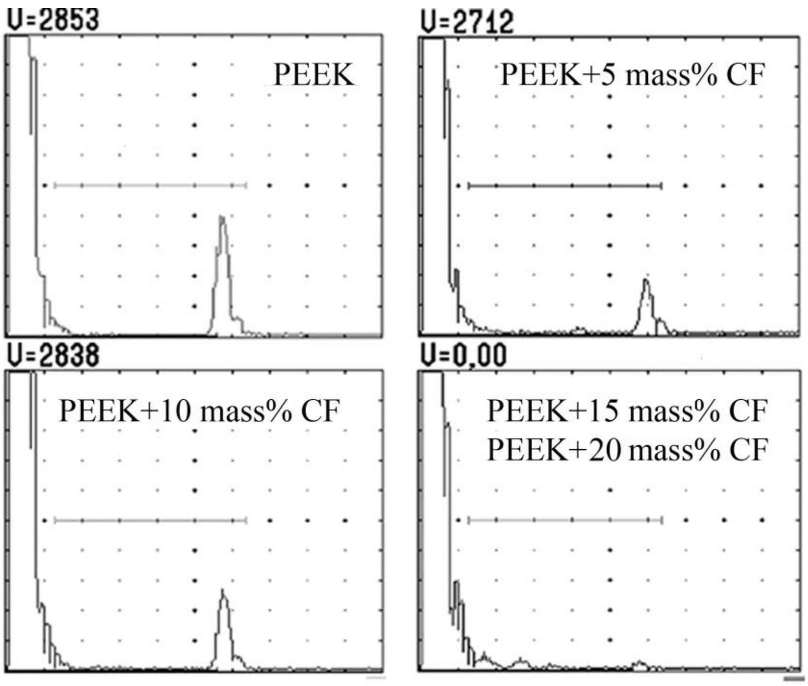


Fig. 5. Pulses of reflected "bottom" signals

Unfilled polymers and composites are characterized by lower speeds of ultrasonic wave propagation in the volume that allows to study samples of small thickness (3-4 mm). In this regard, the evaluation of the reflected "bottom" pulse, the speed of wave propagation, as well as the length of the ultrasound path was carried out on the samples made of PEEK and carbon fiber based on it [11].

The speed of propagation of the ultrasonic wave in the CP varied in the range of 2712-2838 m / s, the amplitude of the reflected signal was in the range of 90%. As it can be seen from Fig. 5 with an increase in the percentage of CF up to 15-20 mass% in the polymer binder the burst from the reflected pulse is absent on the screen of the device, that is, the defect (accumulation of fiber) completely covers the ultrasonic beam [12].

Conclusions

Analysis of the results of tribological studies of developed PCM showed that the use of Toray T700 carbon fiber as a filler for aromatic polyetheretherketone is a promising way to improve its tribological properties: reducing the coefficient of friction and wear by 1.5 and 1.8 times, respectively. When the percentage of carbon fiber (15-20 mass%) increases, it becomes difficult to distribute the binder on its surface evenly. Therefore, tribotechnical characteristics are improved only until the achievement of effective (10 mass%) filling, after which they decrease; this can be explained by the increase in defects of the material due to the dominant loosening at the boundary that confirms the results of ultrasonic control and microhardness measurement. Based on the obtained results, a composite with an effective carbon fiber content can be recommended for the manufacture of plain bearings (agricultural, automotive and textile) that operate in friction conditions without lubrication.

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Буря О.І., Томіна А.-М.В., Начовний І.І. Вплив вуглецевого волокна на триботехнічні характеристики поліефірефіркетону

Суперконструкційні термопластичні полімери, у тому числі поліефірефіркетон, сьогодні активно використовуються у багатьох галузях промисловості. Проте, досить високий коефіцієнт тертя та недостатня зносостійкість обмежує його використання у вузлах тертя машин і механізмів. У статті розглянуто вплив вуглецевого волокна Toray T700 на триботехнічні характеристики ароматичного поліефірефіркетону марки Victrex150G. У результаті проведених досліджень, встановлено що розроблені вуглепластики, перевершують базовий полімер за коефіцієнтом тертя та зносостійкістю у 1,2-1,54 і 1,7-8,8 відповідно, що обумовлено утворенням на сталевому контртілі стабільної «плівки переносу» (так званого антифрикційного шару): дрібнодисперсні частки полімерної матриці та подрібнених продуктів зношування вуглецевого волокна проникають до мікровпадин контртіла. Підтвердженням сказаного служить той факт, що шорсткість вуглепластиків у порівнянні з базовим полімером зменшилася на 50%. Найбільше покращення трибологічних властивостей спостерігається при вмісті вуглецевого волокна 10 мас.%, після чого вони погіршуються, що можна пояснити зростанням дефективності матеріалу за рахунок домінуючого розпушення на межі поділу «полімер-волокно», що і підтверджують результати вимірювання мікротвердості та ультразвукового контролю. Отримані результати досліджень, свідчать що композит, із ефективним вмістом вуглецевого волокна (10 мас.%) може бути рекомендована для виготовлення деталей рухомих з’єднань машин і механізмів, що працюють в умовах тертя без змащення у різних сферах промисловості: сільськогосподарській, автомобільній та текстильній тощо.

Key words: поліефірефіркетон, вуглецеве волокно, зношування, коефіцієнт тертя, ультразвуковий контроль

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E-mail: tribosenator@gmail.com

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Microgeometrical characteristics of electrospark coatings in the initial state

V.V. Tokaruk, O.O. Mikosianchyk, R. G. Mnatsakanov, N.O. Rohozhyna

National Aviation University, Ukraine
E-mail: oksana.mikos@ukr.net

Abstract

Microgeometric parameters of the effect of discrete electrospark coatings on their stress-strain state have been evaluated for the case of using a combined technology of modification of duralumin D16, which includes the technique of electrospark alloying with subsequent surface plastic deformation of coatings formed. According to the profilograms of discrete electrical coatings, the curves of the bearing surface (Abbott curves) were constructed and the parameters that drastically affect tribological characteristics of the coatings were determined. It was shown that modification of duralumin D16 with a combined electrospark coating VK-8 + Cu reduces the arithmetic mean height of peaks in the top portion of the profile by 4.4 and 3.2 times, doubles the arithmetic mean depth of the profile core irregularities, increases the arithmetic mean depth of profile valleys by 1.8 and 1.1 times, in comparison with electrospark coatings from hard alloy VK-8 and copper, respectively. These parameters help to reduce the period of running-in of the contact surfaces strengthened by the combined electrospark coating VK-8 + Cu, increase their bearing capacity, contact durability and specific oil consumption. On the basis of the finite element analysis method of the Nastran software complex, a model of the stress-strain state of a discrete coating/base was designed and distribution of the main normal stresses was determined for a coating compactness of 60% under a normal load of 600 N. The performed modeling revealed advantages of a combined technology for formation of wear-resistant electrospark coatings, which consists in turning residual tensile stresses into compressive ones. When modifying the duralumin D16 with a VK-8 + Cu coating, on the coating surface and in the base material, compressive stresses (-93 MPa and -20 MPa, respectively) are formed, which provides a decrease in wear of the modified surface by two times compared to unmodified duralumin D16.

The practical importance of the work consists in improving the wear resistance of aluminum alloy through its surface modification with functional coatings using energy saving technologies.

Key words: elektrospark alloying, discrete coating, Abbott curve, stress-strain state.

Introduction

The widespread use of aluminum and aluminum-based alloys in transport engineering is determined by high specific strength, increased corrosion resistance, as well as the ability to damp vibrations and high energy absorption. When choosing a structural material for tribocoupling, the main requirements are the ability to provide high antifriction and mechanical properties during operation. An efficient way to improve the mechanical characteristics of aluminum alloys is their surface hardening. A promising trend for modifying a surface layer is the use of the method of electrospark alloying (ESA), which has a unique set of advantages that meet modern requirements: low energy consumption, environmental safety, simplicity of technology (no special working medium and no preliminary surface preparation are needed) and high adhesion strength to the base. Electrospark processing provides the formation of a layer on the workpiece surface which has a structure and properties different from those in the initial state, depending on the parameters of the spark discharge, composition of the electrode material, workpiece material and other factors. The use of ESA to increase the microhardness of near-surface layers and the wear resistance of aluminum alloys is a topical trend in the current applied science.

Literature review

The solution to the problem of hardening the surface layer of aluminum alloys will provide an increase in wear resistance and fatigue strength, change in the magnitude and sign of residual stresses, etc. Despite the obvious advantages of the ESA method, it has some disadvantages, which include both an increase in the roughness of the modified layer and limitation for the applied coating depth. The main reasons for the latter are the occurrence of residual tensile stresses, including those due to the formation of new phases in the alloyed layer with different thermal expansion coefficients, which increases the likelihood of cracking in the applied coating [1].

Taking into account the disadvantages of continuous electrospark coatings (ESC), consisting in cohesive cracking and adhesive delamination, a technology of hardening and restoration by applying coatings of a discrete structure has been developed at H.S. Pisarenko Institute for Problems of Strength of NAS of Ukraine. The main advantage of discrete coatings is the ability to create conditions for regulating the temperature regime, achieving the lowest coefficient of friction and wear, to control and minimize the stress-strain state (SSS) of the surface via changing the continuity and dimensions of discrete areas on the base surface, as well as via selecting a set of materials with required physical and mechanical characteristics [2].

To reduce the initial roughness of electrospark coatings and to change the magnitude and sign of residual stresses, it is advisable to use ESA technology combined with surface plastic deformation (SPD), which makes it possible to form a surface layer with high hardness, wear resistance, low roughness and increased fatigue strength [3, 4].

It has been shown [5] that during ESA residual tensile stresses arise in the surface layer down to 0.2 mm deep. As a result of the subsequent hardening of the formed electrospark coatings thanks to SPD by rolling with a ball, the deformation curves change markedly: compressive stresses up to 520 MPa at a depth of to 0.9 mm are formed in the surface layer. Similar qualitative results were obtained in [6], where it was experimentally established that during plastic deformation of electrospark coatings, residual tensile stresses (43...59 MPa) turn into residual compressive stresses (–34… –80 MPa) down to a coating depth of 79–210 μm. This phenomenon occurred due to strain hardening caused by structural changes (in particular, by increase in the density of dislocations).

The performance characteristics of machine parts and mechanisms to a great extent depend on the parameters of the working surface quality, among which such microgeometrical characteristics as waviness, roughness, central height of microirregularities et al. should be mentioned first of all alongside with physical and mechanical properties (thickness, structure and phase composition of the hardened layer) [7]. The parameters of the surface layer quality directly determine tribological characteristics of triboelements. An increase in the coefficient of friction with increasing height of roughness parameters and its decrease along with wear, an increase in contact vitality with increasing the bearing curve of the profile have been established in the work [8].

The roughness of the surface layer directly affects the service life of friction pairs since microirregularities act as concentrators of stresses and may lead to a decrease in fatigue resistance. Practical operation of machines and mechanisms has shown that the wear intensity of the contact surfaces is dependent on the duration of running-in period, oil consumption, area of actual contact and other parameters determined by the curve of the bearing surface (Abbott curve) [9].

Thus, study of the features of modified layer formation on the surfaces of workpieces under a combined technology of ESA and PPD, the establishment of relationship between the substructure parameters, SSS of the modified layer and its tribological characteristics is an urgent task in terms of developing technological recommendations for strengthening parts in order to increase the overhaul life of units and assemblies.

Purpose

The purpose of the work was to evaluate microgeometric parameters of discrete electrospark coatings and their SSS using a combined technology for modifying duralumin D16.

Methods

Model annular samples of friction pair were made of steel 30KhGSA and duralumin D16, on the surface of which test alloys were deposited by the electrospark method using a standard industrial installation "Elitron 22A" in air at a specific duration of surface processing 1 min/cm2. The electric pulse duration was 200 μs.

As coating materials, hard alloy VK8 and copper, the physical-mechanical properties of which are listed in Table 1, were used.

Table 1

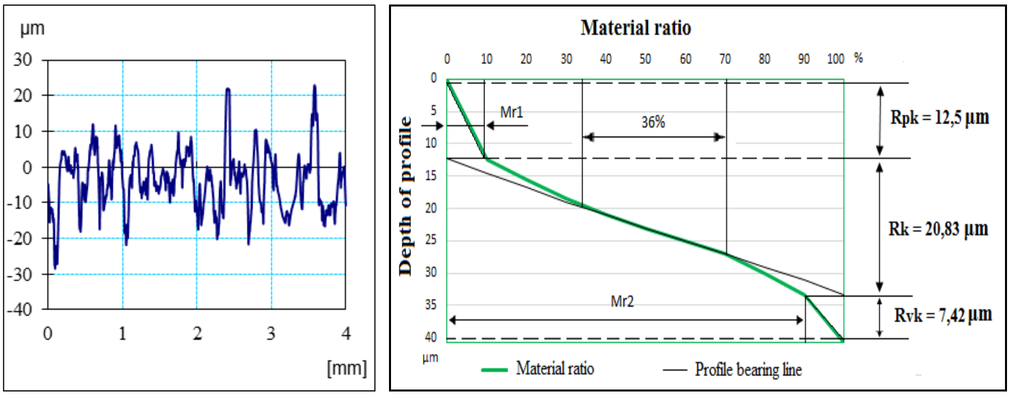
Physicomechanical properties of duralumin D16, alloy VK8, and Cu

Properties	D16	VK8	Cu
Density, kg/m^3	2800	14600	8940
Linear expansion coefficient, $\cdot 10^{-6}$, K^{-1}	23	45	16.7
Coefficient of thermal conductivity, Wt/(m·K)	170	54	401
Specific heat, J/(kg·K)	1000	150	385
Young's Module, $\cdot 10^{11}$ Pa	0.71	6.0	1.15
Shear Module, $\cdot 10^{11}$ Pa	0.27	2.5	4.24
Poisson's ratio	0.3	0.196	0.33

Parameters of surface microrelief profile were determined according to the international standard DIN 4776 [10].

Results

On the basis of ESC profilograms, Abbott curves were constructed and the main parameters of the surface profile were analyzed (Fig. 1, Table 2).



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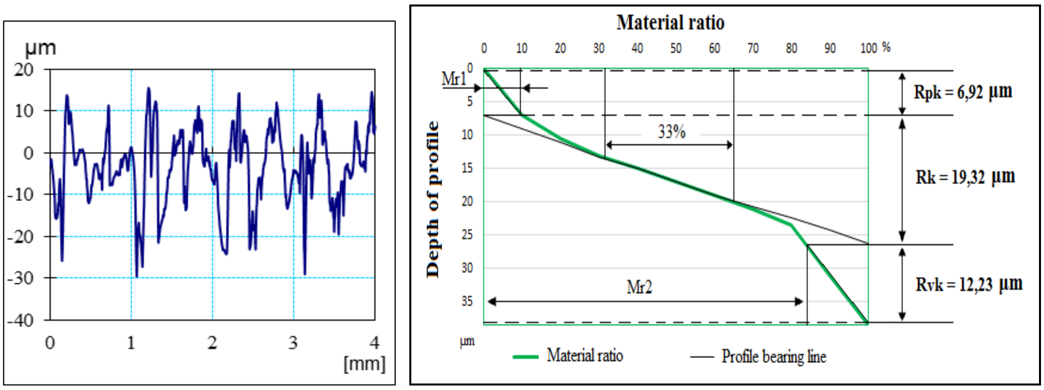

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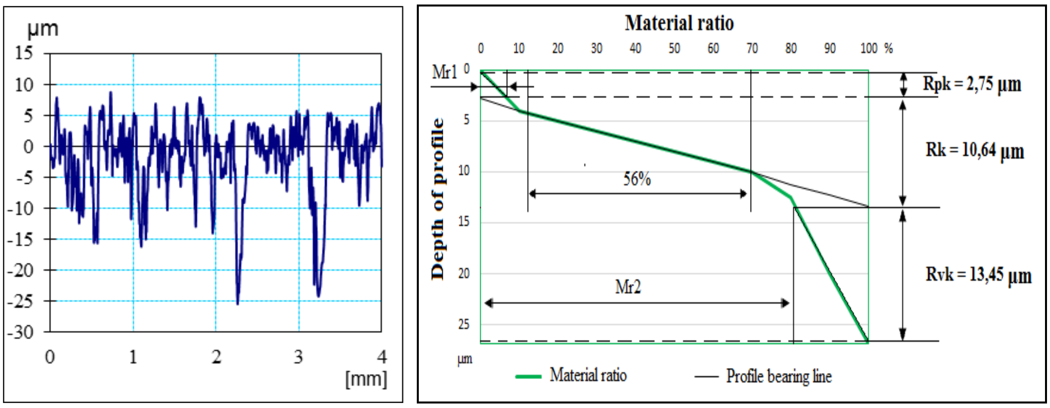

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Fig. 1. Profilograms of the ESC surfaces and functional parameters for the roughness profile from the Abbott curve: (1) VK-8; (2) Cu; (3) VK-8 + Cu.

Table 2.

Functional parameters of the profile of surface microrelief roughness

Parameters of profile of surface roughness	Type of electrospark coating		
	VK-8	Cu	VK-8 + Cu
R_{pk}, arithmetic mean height of the profile top peaks, μm	12.15	6.92	2.75
R_k, arithmetic mean core depth of profile microirregularities, μm	20.83	19.32	10.64
R_{vk}, arithmetic mean depth of profile valleys, μm	7.42	12.23	13.45
R_a, arithmetic mean deviation of profile, μm	6.29	6.53	4.2
Mr1, material ratio that determines the upper limit of core roughness, %	8	10	7
Mr2, material ratio that determines the lower limit of core roughness, %	89	83	81
Central part of mean relative bearing profile length, %	36	33	56
Q, specific surface oil consumption, mm^3/cm^3	0.041	0.104	0.128

An important stage in the initial operation of machine parts is the duration of running-in period. It is in this stage that the primary condition for contacting triboelements is growth of the actual contact area. It is possible to reduce the running-in period by minimizing the profilogram portion that corresponds to the peaks in the upper part of the profile. According to Table 2, for the combined coating VK-8 + Cu parameter R_{pk} is 2.75 μm, which indicates the most effective ability of this coating type to shorten the running-in period.

The parameter R_k allows one to predict the operational properties of the surface and directly affects the service life of triboelements, since this zone in the core of the profile microirregularities determines the bearing capacity and load distribution in the contact. As the combined coating VK-8 + Cu is characterized by a decrease in this parameter on average twice compared to the other ESC studied, it is possible to predict its high efficiency after the formation of microrelief upon using the combined technology of ESA and PPD. The level of coincidence of the region of maximum increase in material ratio of the surface microrelief profile on the Abbott curve and the reference line of the surface roughness profile for VK-8, Cu, VK-8+Cu coatings is 36; 33; 56 %, respectively (Fig. 1). According to the method of evaluation of this parameter by the DIN 4776 standard, its recommended values are around 40%. Only for the VK-8 + Cu coating, increase in this parameter by 1.4 times in comparison with the normalized value was established. The obtained results indicate that the combined coating VK-8 + Cu in the initial state is characterized by the maximum material increase in the core zone of the surface profile, which is decisive in predicting the service life of the contact surface.

An important Abbott curve parameter is the arithmetic mean depth of the profile valleys, which determines the oil consumption by the tribological surface. The specific oil consumption of the surface was calculated by the formula [9]:

$$Q = \frac{R_{vk}}{20}\left(1 - \frac{M_{r2}}{100\%}\right), \qquad (1)$$

where R_{vk} is the arithmetic mean depth of the profile valleys and M_{r2} is the material ratio that corresponds to the lower limit of core roughness, %.

According to Table 2, the calculated data on specific oil consumption for the combined ESC VK-8+Cu are 3.12 and 1.23 times higher than the similar parameters for VK-8 and Cu coatings, respectively. The parameter Q directly affects antifriction characteristics of the coatings studied: for VK-8, Cu, VK-8 + Cu the coefficient of friction in the contact is 0.17; 0.13; 0.11, respectively. Therefore, the VK-8 + Cu coating in terms of the surface microrelief profile R_{vk} will be characterized by high lubrication and antifriction properties, which is a necessary condition for increasing the durability of tribocoupling under operation conditions in a lubricating medium.

The paper indicates reasonability of using the combined technology for duralumin D16 modification, which includes ESA with subsequent treatment of the formed coatings by SPD. The method of finite element analysis, which is implemented in the Nastran software package, was used to model the electrospark coating density and evaluate its SSS. The studied ESCs were applied onto duralumin D16 with a compactness of 60%. When modeling the SSS of discrete coatings, the residual tensile stresses on the surface of a unit coating were revealed, which were 99, 17 and 57 MPa for coatings VK-8, Cu and VK-8 + Cu, respectively. Since such stresses can reduce wear resistance of the contact surfaces, SPD was performed after ESA by technique of static embossing with a maximum load of 190 MPa ($\sigma_T^{0,7}$ for D16). The combined technology was used in order to increase the tribological ESC properties through turning the residual tensile stresses in the formed ESCs into residual compressive stresses after SPD (Table 3, Fig. 2).

Table 3

Distribution of the main normal stresses in the electrospark coating/base after electrospark alloying (ESA) and subsequent processing of the formed coatings by surface plastic deformation (SPD)

Coating material	Distribution of main normal stresses, σ_z, MPa					
	On ESC surface		At ESC/base (D16) boundary		In the base (D16) at 150 μm depth	
	ESA	ESA+SPD	ESA	ESA+SPD	ESA	ESA+SPD
VK-8	99	-20	47	37	2	-2
Cu	17	-97	5	-4	-2	-7
VK-8 + Cu	57	-93	27	17	2	-20

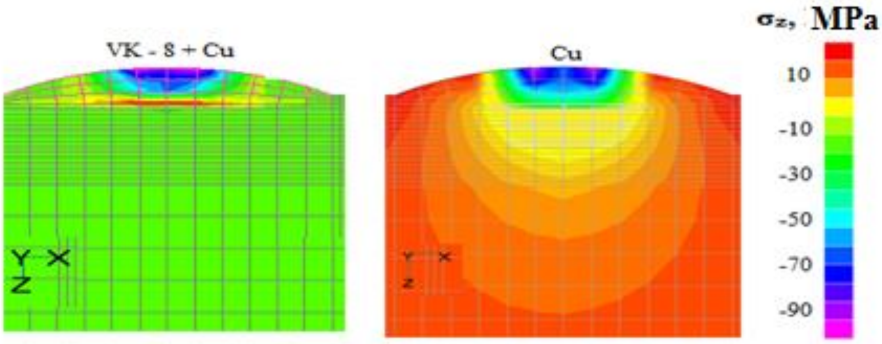

Fig. 2. Distribution of the main normal stresses in ESC/base upon using a combined technology for modification of duralumin D16.

The performed simulation of SSS of a discrete ESC/base has revealed the following advantages of using the combined technology for forming wear-resistant ESCs: on the coating peaks the magnitude and sign of residual stresses change, that is, after ESC tensile stresses turn into compressive ones; when hard alloy VK-8 + copper are used as a coating, the localization of the main normal stresses is observed in the coating formed, in contrast to the coating from copper alone; in the base material from duralumin D16 modified with a coating VK-8 + Cu, compression stresses are formed. These factors increase the wear resistance of contact surfaces: when rubbing in sliding conditions (tests were conducted on a friction machine 2070 SMT-1 for 240 min in the mode of maximum lubrication with an oil consumption of 1.2 l/h; one sample D16 + coating rotated with a frequency of 400 min-1, and the other one (stationary, steel 30HGSA) was installed coaxially, their end faces were pressed together with an axial load of 600 N; as a lubricating medium, motor oil M10G2K (GOST-8581-78) was used), it was established that wear of the contact surface D16 + VK-8 increased by 4.6 times, while modification of the base with Cu coating or combined coating VK-8 + Cu provided wear reduction by 5 and 2 times, respectively, compared to unmodified (with a coating) base D16.

Conclusions

According to the microgeometric parameters of the microrelief profile of discrete electrospark coatings, Abbott curves have been constructed and the parameters that influence coating wear resistance most of all have been determined. In particular, reduction of the arithmetic mean height of the peaks in the upper part of the profile shortens the running-in period for the contact surfaces; growth of the arithmetic mean depth of the core of the profile micro-irregularities provides an increase in load-bearing capacity and determines the load distribution in the contact; increase in the arithmetic mean depth of the profile valleys is the main prerequisite for increasing the specific oil consumption of the surface and ensuring high lubrication and antifriction properties of the tribocontact. The application of the developed combined technology to forming discrete wear-resistant coatings on duralumin D16 is proposed, which includes electrospark alloying followed by surface plastic deformation, which provides the formation of residual compressive stresses and localization of the main normal stresses in the coating formed.

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Токарук В.В., Мікосянчик О.О., Мнацаканов Р.Г., Рогожина Н.О. Мікрогеометричні характеристики електроіскрових покриттів в вихідному стані

Проведена оцінка мікрогеометричних параметрів дискретних електроіскрових покриттів на їх напружено-деформованого стану при використанні комбінованої технології модифікування дюралюмінію Д16, яка включає метод електроіскрового легування з наступною поверхнево пластичною деформацією сформованих покриттів. За профілограмами дискретних електроіскрових покриттів побудовані криві опорної поверхні (криві Аббота) та визначені параметри, які найбільше впливають на триботехнічні характеристики покриттів. Визначено, що модифікування дюралюмінію Д16 комбінованим електроіскровим покриттям ВК-8+Cu забезпечує зменшення середньої арифметичної висоти виступів верхньої частини профілю в 4,4 і 3,2 рази, зростання середньої арифметичної глибини серцевини мікронерівностей профілю в 2 рази, збільшення середньої арифметичної глибини впадин профілю в 1,8 і 1,1 рази, в порівнянні з електроіскровими покриттями твердого сплаву ВК-8 та міді відповідно. Дані параметри сприяють скороченню періоду припрацювання контактних поверхонь, зміцнених комбінованим електроіскровим покриттям ВК-8+Cu, підвищують їх несучу здатність, контактну довговічність, питому маслоємність поверхні.

На основі методу скінченно-елементного аналізу програмного комплексу Nastran проведено моделювання напружено-деформованого стану дискретного покриття - основи та визначено розподіл головних нормальних напружень при щільності нанесення покриття 60% та нормальному навантаженні 600 Н. Проведене моделювання встановило переваги застосування комбінованої технології формування зносостійких електроіскрових покриттів, які полягають в зміні залишкових напружень розтягу на напруження стиску. При модифікуванні дюралюмінію Д16 покриттям ВК-8 + Cu на поверхні покриття та в матеріалі основи формуються напруження стиску (-93 МПа та -20 МПа відповідно), що забезпечує зниження зносу модифікованої поверхні в 2 рази, в порівнянні немодифікованим дюралюмінієм Д16.

Практична значимість роботи полягає в підвищенні зносостійкості алюмінієвого сплаву шляхом його поверхневого зміцнення функціональними покриттями з застосуванням енергозберігаючих технологій.

Ключові слова: електроіскрове легування, дискретні покриття, крива Аббота, напружено-деформований стан.

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Website: http://tribology.khnu.km.ua/index.php/ProbTrib

E-mail: tribosenator@gmail.com

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Investigation of tool wear resistance when smoothing parts

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

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

Abstract

The article discusses the method of surface plastic deformation of steel parts by smoothing. The positive influence of this method on the wear resistance of the tool has been established under conditions of intense wear and with abundant lubrication.

Key words: wear, durability, tool, surface plastic deformation, friction pair, smoothing.

Introduction

The smoothening method is ideally suited to the hardening treatment of surfaces of revolution, using a diamond indenter-smoother with a spherical working surface. Despite the unique properties of diamond as a tool material (high hardness, increased wear resistance and compressive strength), its use is limited by an increased tendency to chemical interaction with structural materials, for example, with low-carbon steels, titanium and its alloys, etc. Lack of lubricating coolants in the burnishing zone only exacerbates this disadvantage of diamond tools [1-3].

The peculiarity of diamond burnishing as a method of sequential local action of a moving indenter on the workpiece surface being processed in the conditions of their mass production is considered as a disadvantage due to low processing productivity [4].

The technological advantages of the burnishing process are obvious, therefore, in this work they are used, but in a technical design with a significantly higher processing performance [5].

Research methodology

As the main criterion for choosing rational conditions for wide burnishing, the roughness of the machined surface of the parts was used, which is provided during the tool life. The durability of the ironing tool has been classified as the time of continuous operation during which it becomes functionally unusable. This condition can be identified as irreversible changes in the topography of the tool working surface through the wear area [6, 7].

To determine the wear area of the spent smoother, a special technique was proposed, which is based on digital processing of surfaces with different reflectivity characteristic of the initial and worn conditions.

The technique for quantifying the area of the worn surface of the tool includes the following steps:

1. Digital photographing of the working surface of the tool on a special stand.

2. Processing the bitmap image of the working surface of the tool in the graphics editor Adobe Photoshop in order to increase the contrast and prepare a digital photograph of the working surface of the smoother to determine the actual wear contact spot in the IZNOSOMER program.

Research results

The burnishing process was carried out on samples made of materials: steel 40 and high-strength cast iron VCh 75-50-03. The samples were pretreated by grinding. The initial roughness of the samples from steel 40 R_a = 0.5 µm, from cast iron R_a = 0.85 µm.

When burnishing samples of steel 40 and high-strength cast iron VCh 75-50-03 for all 3 studied burnishing cycles, an extreme relationship between the roughness of the treated surface and the force on the smoother is observed [8].

It has been established by experiments that the minimum values of the roughness of the processed surface in terms of Ra occur at P = 210 N/mm for steel 40 and at P = 410 N/mm for VCh 75-50-03 cast iron, regardless of the number of burnishing cycles. This pattern suggests that the formation of the roughness of the treated surface is influenced by the processing time and pressure on the surface to be smoothed, therefore, the reason lies in the mechanism of plastic deformation [9].

In Fig. 1, a shows the obtained experimental dependence of the surface roughness of a part made of steel 45 on the length of the path traveled by the tool for tool materials: composite 05IT, leucosapphire, niborite, and in Fig. 1, b - dependence of the surface roughness of a part made of VCh 65-50-03 cast iron on the length of the path traveled by the tool made of composite 05.

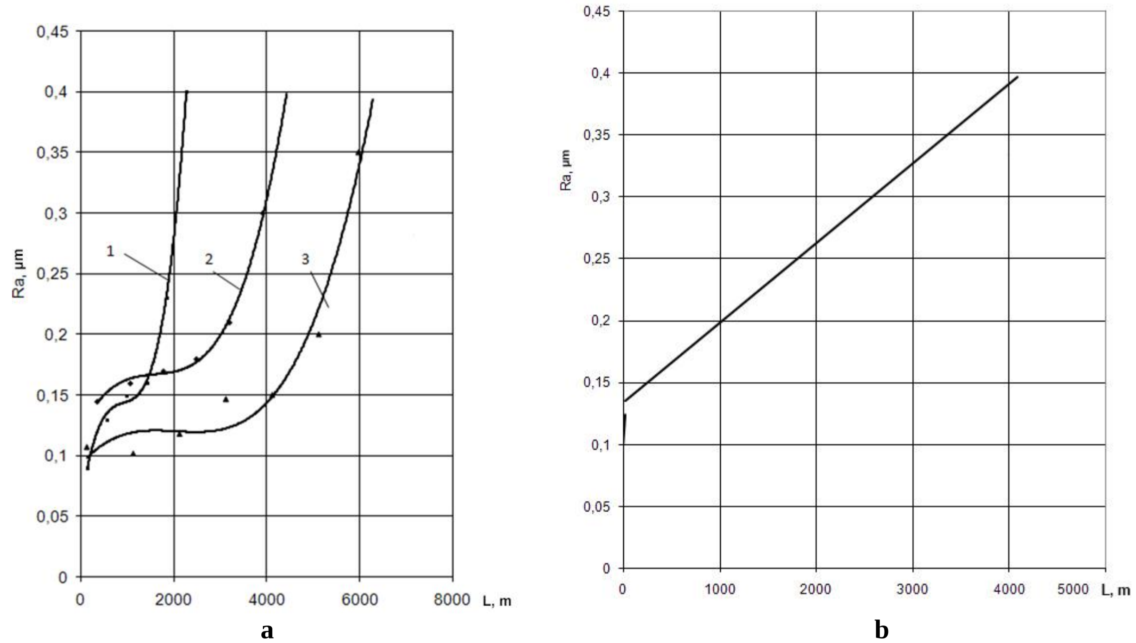


Fig. 1. Dependence of the roughness of the sample during smoothing on the length of the path traveled by the tool made of various materials

As a result of the studies, it was found that the superhard material niborite (tomal 10) has the greatest resistance when processing steel 45, its resistance is 6.3 km. Resistance for other materials when processing steel 45 is 2.3 km for leucosapphire, and 4.4 km for composite 05IT.

The choice of a specific tool material must be made for economic reasons for each material of the workpiece.

Experiments have also shown that the performance of the smoother is increased when using a hard alloy with a reduced dispersion of the carbide phase [10]. The application of wear-resistant coatings, performed in this work, did not give a tangible increase in the durability of carbide tools.

A two-factor experiment was carried out in production conditions, which simulated the joint and interrelated influence of the burnishing force and the number of loading cycles on the quality of processing of the gland journals of crankshafts made of ductile iron. The results turned out to be adequate to the patterns established in the laboratory.

Comparison of the results of experimental studies and calculations using the energy model of wear. A comparative assessment of the data on the sizes of the wear areas of the working surfaces of smoothers made of various tool materials was performed, which were obtained experimentally and by calculation using the energy wear model.

In Fig. 2 shows the dependence of the area of wear on the distance traveled by the tool during processing. Curves 1 and 3 were obtained experimentally according. The critical value of the wear area Scritich was determined as the state of the tool that was not able to provide the required roughness during machining (with the required $R_a = 0.4$ µm, $S_{critical} = 2.5$ mm^2).

Curve 2 was obtained by a theoretical method when solving the energy model presented in the second chapter, while the empirical coefficient of resistance K resistance = $0.375 \cdot 10^{-2}$).

Curve 3 was obtained theoretically using the energy model for a new group of tool materials H10F after introducing the necessary empirical coefficients into it when plotting curve 2. It can be seen from the graphs that the error between the experimental and calculated wear areas is not large (less than 20%), while the curves wear corresponds to the classical, and consist of three main stages: running-in, normal operation, catastrophic wear [11].

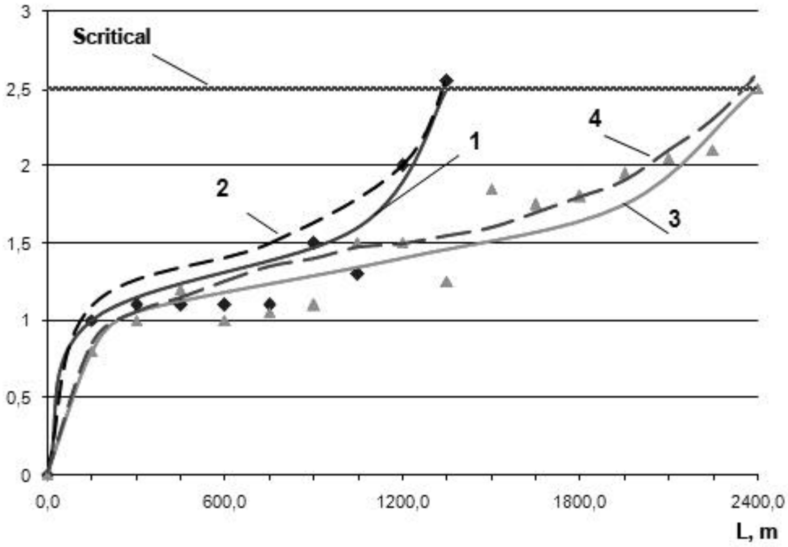
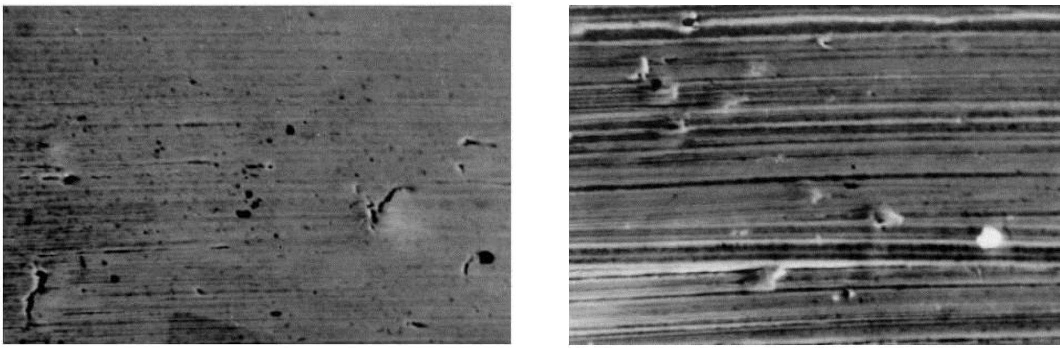


Fig. 2. Curves of the dependence of the area of wear on the traveled path of the tool in the process of wide burnishing

According to the results of a comparative assessment of the data obtained by calculation and experiment, one can recognize their agreement as good. For example, if we compare the sizes of the wear areas of the working surface of smoothers made of various tool materials, calculated according to the energy model of wear and obtained by measuring in real conditions of smoothing, then the difference between them does not exceed 25%, averaging 9.3% according to the results of measurements in 5 different smoothing modes.

Technological features of smoothing of ductile iron with spheroidal graphite. The technological features of the process of wide burnishing of high-strength cast iron with spheroidal graphite (for example, VCh 75-50-03 cast iron), which is characterized by low plasticity, increased hardness and a narrow range of deformation stresses from elastic deformation to its destruction, are revealed [12, 13].

In fig. 3 shows photomicrographs of the machined surface of a ductile iron crankshaft after wide burnishing and polishing with an abrasive belt. From the point of view of the microgeometry of the surface and the need for its running-in at the initial stage of wear, smoothing treatment turned out to be more preferable than polishing.



a **b**

Fig. 3. Surface after smoothing (a) and polishing (b) x300

Under the selected burnishing conditions, the surface layer of parts made of high-strength cast iron has a slight hardening - in terms of the degree of work-hardening, an increase of up to 10% at a work-hardening depth of 4 ... 6 μm.

Investigation of the wide burnishing process on specimens of hardened case-hardened steel 18KhGT. It was found that for smoothing parts made of case hardened 18KhGT steel, it is advisable to use smoothers with a working part made of polycrystalline plates of composite 05 with a radius of 2 mm, which, under optimal loading conditions, provides a roughness of the processed surface to R_a = 0.05 μm without signs of over-hardening. In the case when the initial surface roughness increases before smoothing, it is necessary to increase the pressure on the tool.

Conclusions

The criterion of tool durability is determined by its functional purpose of smoothing as a method of predominantly improving the roughness of the workpiece surface being processed. If the specified requirements for the height of microroughnesses on the machined surface (for example, the value of the R_a parameter) are not met, the smoothing tool is recognized as unsuitable for further work.

The process of tool wear in the work is considered as a transformation of the microgeometric topography of its working surface as a result of the adhesive interaction of two metal bodies under conditions of dry sliding friction using the application effect. The essence of this effect lies in the imposition of the microrelief of the working surface of the smoother when rolling on the workpiece surface with the accompanying process of plastic flow of the surface layer, which allows predicting the tool life.

Comparative evaluation of the data on the sizes of wear areas of the working surfaces of smoothers made of various tool materials, which were obtained experimentally and by calculation using the energy wear model, showed good coincidences of the wear area of the smoother: the maximum difference is 25% with an average error of 9.3%.

Revealing the thermal pattern of wide burnishing allows you to develop technological restrictions on the processing process in terms of two factors. First, to prevent possible negative structural and phase transformations in the surface layer of the burnished part with a subsequent decrease in its quality and operational reliability. And, secondly, to reduce the intensity of tool wear, especially in the absence of a beneficial effect of lubricating cooling process fluids.

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Марченко Д.Д., Матвеева К.С. Исследование износостойкости инструмента при выглаживании деталей.

В статье рассмотрен метод поверхностного пластического деформирования стальных деталей выглаживанием. Установлено положительное влияние этого метода на износостойкость исчнтрумента в условиях интенсивного изнашивания и при обильной смазке.

Ключевые слова: износ, стойкость, инструмент, поверхностная пластическая деформация, пара трения, выглаживание.

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Reduction of oxides formation at surfact depositsitson of wear-resistant alloys

V. Chigarev[1], Yu. Logvinov[2*]

[1]*Mariupol State higher educational institution 'Priazovsky state technical university'* Mariupol, *Ukraine*
[2*]*Mariupol institute Interregional Academy of Personnel Management city of Mariupol. Ukraine*
[*]*E-mail:* 07log07@gmail.com

Abstract

The article deals with the issues of reducing the content of harmful substances when surfacing alloyed wear-resistant alloys. Studies have been carried out to determine the possibility of reducing the formation of oxides during surfacing of high-alloy wear-resistant alloys of the sormite type using a closed filter-ventilation system, which ensures minimal losses of alloying elements during the formation of the deposited layer. The loss of alloying elements during surfacing is influenced by a number of metallurgical and technological factors, including the share of the base metal in the deposited, surfacing modes, oxidation processes during melting of the electrode material and in the melt of the weld pool when interacting with the surrounding gas environment.

To reduce the oxygen content in the gas-air mixture formed during the surfacing process, special absorbent substances are used in a closed filtering and ventilation system, which reduce the course of oxidative processes with the formation of oxides of alloying elements. At the same time, the gas-air mixture is taken from the zone of arc burning and the weld pool, filtered through a system of special filters, in which solid and gaseous components of the welding aerosol are removed, after which the purified gas mixture is used as gas protection during surfacing.

We used powder tapes containing a mechanical mixture of powder components and a complex-alloyed alloy in the core. A complex-alloyed alloy, an alloy previously melted in an induction furnace, containing the necessary alloying elements. Particles of the required sizes were obtained by hydrogranulation, which were then introduced into the core of a flux-cored tape. The indicated flux-cored strips provided the same chemical composition of one alloying system in the deposited layer. After surfacing, the chemical composition of the deposited metal was determined for the content of carbon, manganese, silicon, nickel. The use of a closed filtering and ventilation system makes it possible to reduce the formation of oxides of alloying elements, which requires the determination of specific parameters for each surfacing process. Creation and use of closed fil'tro vent system (CFVS), serve of the filtered air in area of surfacing and providing safe labour in the workplace of welder. It corresponds the international standard of ISO and norms of European Union. Therefore, to execute a requirement to impermissibility of hit of harmful questions in an atmosphere concordantly Kiotskomuo and to Parisian protocols.

Key words: electrode materials, surfacing, alloying elements, welding aerosols, oxidation processes, closed filter ventilation system, deposited metal.

Introduction

Development of technological process of deposition of wearproof alloys with providing of decline of formation of oxides and losses of alloying elements in a deposition metal. Exposition of basic material. Creation and use of closed fil'tro vent system (CFVS), serve of the filtered air in area of surfacing and providing safe labour in the workplace of welder. It corresponds the international standard of ISO and norms of European Union. Therefore, to execute a requirement to impermissibility of hit of harmful questions in an atmosphere concordantly Kiotskomuo and to Parisian protocols.

Literature review

Substantive provisions on the rational alloying of metal and forming of wearproof phase are in-process [2] Safronov in fundamentals of rational alloying of alloys presented. Substantive provisions are in-process Livshits [3] expounded on alloying of deposition metal, intended for work under various conditions of shock, abrasive wear, and also influence of alloying elements on formation of carbidic phase and matrix - basic constituents of alloy.

Purpose of the article

Development of technological process of deposition of wearproof alloys with providing of decline of formation of oxides and losses of alloying elements in a deposition metal. Exposition of basic material to apply CFVS.

Main materials

For surfacing apply different deposition materials, different welding-technological properties, composition and alloying elements, providing the receipt of the required composition and properties in a deposittd layer.

As a result of melting of electrode metal and flowing of metallurgical processes in the area of burning of arc and welding bath, there is a selection in the atmosphere of different gases with formation of welding aerosols (SA). Formative SA consist of hard constituents of welding aerosol (HCWA) and gaseous constituents of welding aerosol (GCWA). Welding aerosols, contain harmful matters as a dust and gases, different oxides: CO, MNO, SiO_2, Cr_2O_3, NO, N_2O_3, So2, render negative influence on sanitary-hygienic terms in a working area [3-4].

The amount of harmful excretions depends on the modes of cladding, type of electrode material and its composition. For mechanized electric arc deposition powder-like band electrode materials are widely used. At deposition with the use of powder-like ribbon the content ofmaintenance of chemical elements in a deposited metal goes down due to formation of oxides of alloying elements as a result of their co-operating with oxygen of atmospheric air, that has influence on properties weld layer.

For diminishing the contet of oxygen in air-gas mixture, appearing in the process of deposition, the special absorbents in ZFVS, which reduce flowing of oxidizing processes with formation of oxides of alloying elements, are used. Thus air-gas mixture is taken from the area of burning of arc and welding bath, passes filtration through the system of the special filters TSSA and GSSA delete in which, whereupon cleared gas mixture is used as gas defence at deposition [5].

Researches were conducted with the use of powder-like ribbons which had different mandrels, but provided identical chemical compositions of the deposition metal. Powder-like ribbons, containing mechanical mixture of powdery components and complex-alloyed alloy in a rodmandrel, were used. The complex-alloyed alloy (ligature) is the alloy containing the necessary alloyed elements preliminary smelted in an induction stove.

The receipt of particles of the required sizes was produced by gidrogranulyacii, which was after entered in the complement of mandrel of powder-like ribbon. The indicated powder-like ribbons provided identical chemical composition of one system of alloying in a weld layer. Making of powder-like ribbons of necessary sizes was produced on machine-tools which provide the receipt of the One Articulata construction of furnace.

Cladding was conducted on the permanent modes: welding current 700-750 And, tension of arc 28-32 In, cladding 36 mcode/hour. After cladding n surfacing determined chemical composition of deposwited vtnal was was denermined threw on maintenance of carbon, manganese, silicon, nickel. For the receipt of reliable results of estimation produced for 10 measurings for every experiment. In the process of deposition from the area of burning of arc produced the selection of gas environment with the use of ZFVS.

During work of ZFVS different sorbents and filter elements were probed. General information about matters, recommended as a sorbent able to absorb oxygen is presented in table 1 [5].

Table 1

General information about the used sorbents

Name of sorbent	The biggest aesorbed molecules	Kinetic diameter Å
Yugavaralit	C_2H_4	3,6…3,9
Zeolite	$(C_4H_9)_3N$	8,1
Zeolite of W	SO_2	3,6
Zeolite of R- W	NO	3,6
Zeolite of L	$(C_4H_9)_3N$, $(C_4F_9)_3N_1$	8,1
Fozhazit	$(C_2F_5)_3N$	8,0
Stil'bit	H_2O, NH_4	2,6
Mordenit shirokoporistiy	NH_9	2,6
Natrolite	$(C_4F_9)_3N$	10
Zhismondin	N_2; O_2	3,6

The results of researches with the use of ZFVS (with the special sorbents) and different types of alloying charge in composition the rods of powder-like ribbon are smown in a table 2. Application of ZFVS allowed to delete from an air-gas environment, formed in a proces of cladding of TSSA and GSSA, to reduce the content of oxygen with the special sorbents.

Table 2

Maintenance of alloying elements in aweld metal with the use of ZFVS

Type of mandrel of powder-rod ribbon	Type of deposition	Type of surfacing composition of alloying deposition elements is in the metal of guy-sutures, %				
		C	Mn	Si	Cr	Ni
Mechanical mixture of components	Without the use of ZFVS	2,55	1,44	2,4	20,6	2,8
	With the use of ZFVS	2,8	1,8	2,99	21,6	2,92
Complex-alloyed ligatures	Without the use of ZFVS	2,70	1,4	2,04	20,4	2,66
	With the use of ZFVS	2,9	2,12	3,06	24,2	3.80

In 1 and 2 presented is chemical composition of weld metal, got at surfacing with the use of powder-like ribbons cored from mechanical mixture of components and complex-alloyed alloy with the use of ZFVS.

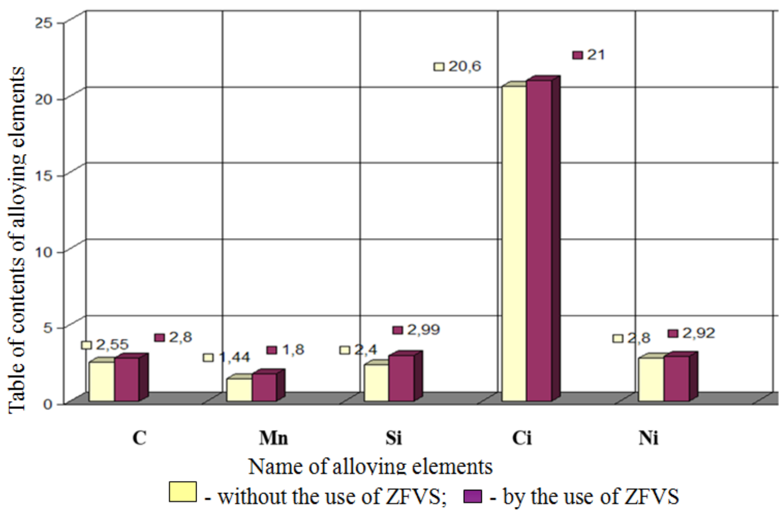

Fig.1. Chemical composition of depositiec metal at deposition a powder-like ribbon, containing mechanical mixture of components in composition a mandrel

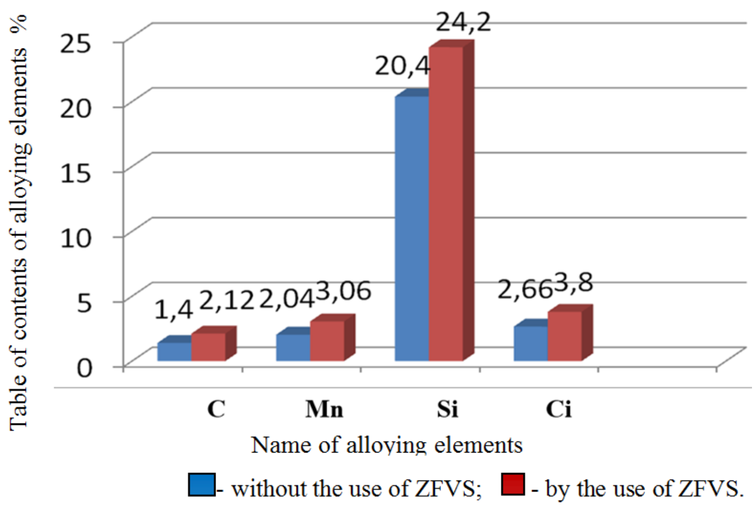

Fig.2. Chemical composition of deposited metal at surfacing a powder-like ribbon, containing the complex-alloyed alloy in Rod 's composition

The results of experiments testify to the reduction decline of oxidization of alloying elements in the process of deposition. At deposition of wear proof alloys it is possible to decrease oxidizing processes, but it is necessary to conduct the choice of sorbents which can maximally absorb harmful excretions, table.2.

Conclusions

1. The use of ZFVS in the area of burning of arc reduces of oxygen and formation of oxides, at the use of the proper sorbent, that is instrumental for preservation alloying elements in a weld metal.

2.Alloying elements in a deposited weld metal will allow to improve process of work-hardening of metallurgical machines, it is the real solution of task of wear of metallurgical machines and are the area of tribologoicheskikh researches.

3.For reduction of flowing of oxidizing processes at surfacing of high wearproof alloys of type of sormayt with the use of ZFVS as a sorbent it is recommended to use zhismondi.

4. Creation and use of closed fil'tro vent system (CFVS), serve of the filtered air in area of surfacing and providing safe labour in the workplace of welder. It corresponds the international standard of ISO and norms of European Union. Therefore, to execute a requirement to impermissibility of hit of harmful questions in an atmosphere concordantly Kiotskomuo and to Parisian protocols.

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Чігарьов В.В., Логвінов Ю.В. Зниження утворення оксидів при нанесенні поверхнево-активних речовин із зносостійких сплавів.

У статті розглядаються питання зменшення вмісту шкідливих речовин при наплавленні легованих зносостійких сплавів. Проведені дослідження з метою визначення можливості зменшення утворення оксидів при наплавленні високолегованих зносостійких сплавів сормітного типу із застосуванням закритої фільтрувально-вентиляційної системи, що забезпечує мінімальні втрати легуючих елементів під час утворення осаджених шарів. На втрату легуючих елементів під час наплавлення впливає ряд металургійних і технологічних факторів, включаючи частку основного металу в наплавленому шарі, режими наплавлення, процеси окислення при плавленні електродного матеріалу та в розплаві зварювального басейну при взаємодії з навколишнім газовим середовищем.

Для зменшення вмісту кисню в газоповітряній суміші, що утворюється в процесі наплавлення, в закритій фільтруючій та вентиляційній системі застосовуються спеціальні абсорбуючі речовини, які зменшують хід окисних процесів з утворенням оксидів легуючих елементів. При цьому газоповітряна суміш береться із зони дугового горіння і зварювального басейну, фільтрується через систему спеціальних фільтрів, в яких видаляються тверді та газоподібні компоненти зварювального аерозолю, після чого очищена газова суміш використовується як захист від газу під час наплавлення.

Ми використовували порошкові стрічки, що містять механічну суміш порошкових компонентів і складний легований сплав в серцевині. Сплавно-легований сплав - сплав, попередньо розплавлений в індукційній печі, що містить необхідні легуючі елементи. Частинки необхідних розмірів отримували гідрогрануляцією, які потім вводили в серцевину порошкоподібної стрічки. Зазначені порошкоподібні смуги забезпечували однаковий хімічний склад однієї легуючої системи у нанесеному шарі. Після наплавлення визначали хімічний склад наплавленого металу за вмістом вуглецю, марганцю, кремнію, нікелю. Застосування закритої системи фільтрації та вентиляції дає змогу зменшити утворення оксидів легуючих елементів, що вимагає визначення конкретних параметрів для кожного процесу наплавлення. Створення та використання закритої фільтрувальної системи фільтра (CFVS), що подає фільтроване повітря в зону наплавлення та забезпечує безпечну працю на робочому місці зварника. Він відповідає міжнародному стандарту ISO та нормам Європейського Союзу. Отже, виконати вимогу про неприпустимість потрапляння шкідливих питань в атмосферу відповідно Кіотського та Паризького протоколам.

Ключові слова: електродні матеріали, наплавлення, легуючі елементи, зварювальні аерозолі, процеси окислення, вентиляційна система із закритим фільтром, наплавлений метал.

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

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Investigation of slippage and wear in rolling bearings of machines

A. Dykha, V. Dytyniuk, M. Dykha

[1]*Khmelnitskyi National University, Ukraine*
**E-mail: tribosenator@gmail.com*

Abstract

The purpose of this work was to study the processes of slipping and wear in the sliding bearings of machines. It is determined that slippage in bearings is the main cause of bearing parts failure according to the criterion of wear. Analytical relations for determining the amount of slip and sliding path in the bearing are presented. For experimental research of sliding in rolling bearings the test installation is designed. Experimental tests on the effect on load slip, sliding speed and lubrication conditions in the bearing were performed. The model of wear of rings of the sliding bearing on the basis of a solution of a wear contact problem is offered. The formulas for calculating wear and parameters of the wear model are obtained. The obtained results are recommended to evaluate the influence of design and technological factors on the durability of rolling bearings by the criterion of wear.

Key words: rolling bearings, slip, experimental installation, lubrication conditions, wear model, wear contact problem

Introduction

The main bearing unit of the machines are rolling bearings. The main causes of bearing failure are: fatigue spalling of raceways; wear of raceways; plastic deformation and creep of raceways. At present, the process of contact fatigue failure of bearings is well studied. Methods for calculating contact strength based on the solution of the contact problem according to Hertz have been developed. Test methods and definitions of damage accumulation models have been developed.

At the same time, many bearings fail due to wear rather than fatigue. This primarily applies to bearings in abrasive and high temperature conditions. There are practically no methods for calculating and testing bearings for wear, which complicates their design.

Methodology for calculations and tests for wear and reliability of bearings are the following stages.

1. The features of the design and technology of the friction unit are studied. The loads on the rolling elements are determined.
2. The contact pressures between the body and the raceway are determined.
3. The sliding path of the ball or roller along the raceway is determined.
4. Selection of a wear model and experimental determination of its parameters.
5. Solving wear-contact problems for bearing parts.
6. Calculations for bearing wear reliability using Gaussian normal distribution.

Thus, one of the main values for calculating and analyzing the process of wear of rolling friction units is the sliding friction path between the contacting bodies.

Literature review

The roller bearing model in [1] was developed to evaluate cage slip, roller slip, film thickness and cage forces for a given bearing geometry and operating conditions. The model takes into account the friction of the cage guide surface, the friction of the roller pocket, and the cage unbalance. Skewed and skewed rollers were not considered. The description of the lubricating film thickness, adhesion forces and pressure is based on the solution of the isothermal problem of elastohydrodynamics.

The article [2] proposes a numerical method for determining the sliding of a cage in high-speed ball bearings with an axial load. The model agrees well with the experimental results for sliding ball bearings. The model is recommended for studying the causes of sliding in loaded ball bearings.

The influence of operating parameters on the slip of the cage in cylindrical roller bearings is considered in paper [3]. The cylindrical roller bearing test bench is designed to measure the movement of bearing elements under various operating conditions. The influence of operating parameters, namely, shaft rotation speed, radial load, lubricating oil viscosity, number of rollers and bearing temperature, on the cage sliding is obtained experimentally.

The slip of the cage and balls of ball bearings used in paper [4] for the main shafts of jet engines is evaluated. A new method has been developed for assessing slip, taking into account the increase in oil temperature caused by slip in the contacts between the ball and the raceway. The analytical results of the study were compared with experimental data.

In [5] the influence of different models of a radially loaded cylindrical roller bearing is investigated using a dynamic model of a bearing assembly. The cage rotation speed, depending on the force between the roller and the raceways, is designed for a wide range of speeds and loads. Comparison of the simulation results with the results of experimental measurements shows that the model is able to predict the operation of the rolling elements under various operating conditions.

Further modeling of sliding in rolling bearings from various points of view was also considered in papers [6-11].

Slip in ball bearings

It is known from experiments that the length of the path of a ball of a ball during rolling is not equal to the length of a circle made up of points of contact. This means that rolling occurs with slippage. In this paper, slippage is necessary to determine the sliding friction path for wear calculations. Determination of the sliding path in rolling with slip in most of the known studies was done by theoretical methods. Determination of slippage by theoretical methods leads to complex mathematical problems, the solution of which again requires simplifications and approximations. Most often, it is difficult to assess the accuracy of these solutions.

It is more rational to experimentally determine the value of the slip coefficient of bearings, taking into account various factors and apply them to other types of bearings.

Consider the basic relations for the rolling of a ball on a plane with slippage.

The rolling friction force is related to the normal load, ball radius and rolling friction coefficient by the ratio:

$$F_r = \mu_r \frac{N}{R}. \tag{1}$$

When the ball is rotated through an angle 2π or a full turn in the absence of slippage, the length of the contact line on the plane will be equal to the circumference of the ball:

$$l = 2\pi R. \tag{2}$$

In the presence of slippage, the rolling friction path will differ from the circumference by an amount Δl.

Attitude:

$$S_c = \frac{\Delta l}{l}, \tag{3}$$

called the slip coefficient. Experimental determination of the slip for a single ball is not difficult.

Let us assume that rolling resistance occurs due to the slipping of the ball along the plane at the points of contact. Thus, the rolling resistance due to surface deformations is neglected.

Slip resistance frictional force:

$$F_s = \mu_s N. \tag{4}$$

We assume that the work of rolling friction forces on the rolling path is equal to the work of sliding friction forces on the sliding path Δl:

$$W_r = W_s. \tag{5}$$

or

$$F_r l = F_s \Delta l. \tag{6}$$

Substituting (1) and (4) into (6), we obtain:

$$\mu_r \frac{N}{R} l = \mu_s N \Delta l . \quad (7)$$

Or, taking into account (3), we obtain:

$$S_c = \frac{\mu_r}{\mu_s R} . \quad (8)$$

Therefore, the coefficient of rolling slip is equal to the coefficient of rolling friction divided by the coefficient of sliding friction.

An example of a ball rolling $d = 12.3$ mm on hardened steel (Fig.1).

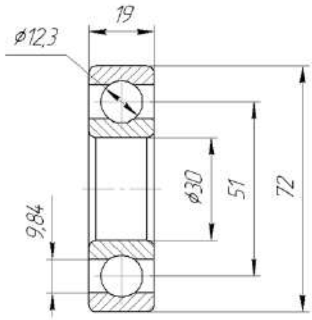

Fig. 1. Dimensional drawing of plain ball bearing

The rolling friction coefficient is assumed to be $\mu_r = 0.01$ mm. Sliding friction coefficient of steel on steel without lubrication $\mu_s = 0.1...0.3$.

Then:

$$S_c = \frac{\mu_r}{\mu_s R} = \frac{0.01}{(0.1...0.3) \cdot 6.15} = 0.016...0.005 .$$

With a cage diameter in the bearing of $d_c = 51$ mm, the sliding friction path for the balls along the raceway per revolution is $D_s = S_c \pi d_c = (0.016...0.005)\pi \cdot 51 = 2.56...0.80$ mm.

The basis of the experimental method

The mechanics of the motion of balls in rolling bearings of machines with a slip is a complex problem in contact mechanics. The complexity is explained by the variety of ball movements: around the rotor axis; rotation around its own axis; spinning; gyroscopic motion; slippage in all contact zones.

Slip mechanics are complicated by the proximity of the ball radii and the radius of the ring track. At the same time, the calculation of rolling bearings for wear requires an accurate assessment of the sliding friction path in contact between the ball and the raceways.

A computational and experimental method is proposed for determining the amount of slip in ball bearings. The basis of the approach is as follows. From the kinematics of the bearings, precise relationships are obtained for the movements of the balls and rings without slipping. On the other hand, experimentally, you can simply measure the number of revolutions of the separator. The difference between the calculated and actual numbers of revolutions of the cage allows you to determine the average value of the ball sliding along the raceway.

The kinematics of rings and a ball in a bearing is considered under the following conditions: the inner ring rotates; the outer ring is stationary; the ball rolls over the rings without slipping. Kinematics are considered to determine the sliding friction path of a ball along the raceways.

For a bearing with a fixed outer ring, the geometric ratio is adopted:

$$V_c = \frac{1}{2} V_1 , \quad (9)$$

where V_c, V_1 is the linear speeds of movement of points of the separator and the inner ring V_1.
The linear speed of the ring is expressed in terms of the number of revolutions by the ratio:

$$V_1 = \frac{\pi d_1 n_1}{60}. \tag{10}$$

Similarly for the linear speed of the separator:

$$V_c = \frac{\pi d_c n_c}{60} = (d_1 + d_0)\frac{\pi n_c}{60}, \tag{11}$$

where d_c is the cage average diameter;

d_1 is the diameter of the inner ring;

n_1 is the the number of revolutions of the inner ring;

n_c is the the number of revolutions of the separator;

d_0 is the ball diameter.

After mutual substitutions and transformations, we get:

$$n_c = \frac{n_1}{2(1 + d_0 / d_1)}. \tag{12}$$

The experimental speed of the separator n_c^* differs from the theoretical speed n_c. The difference between experimental and theoretical rpm is explained by the slippage of the balls along the raceways.

With this in mind, the coefficient of slip in the rolling bearing is determined by the relationship:

$$S_c = \frac{n_c^* - n_c}{n_c^*} = 1 - \frac{n_c}{n_c^*}. \tag{13}$$

Installatio, test procedure and results

An installation for testing rolling bearings for slip is shown in Fig. 2.

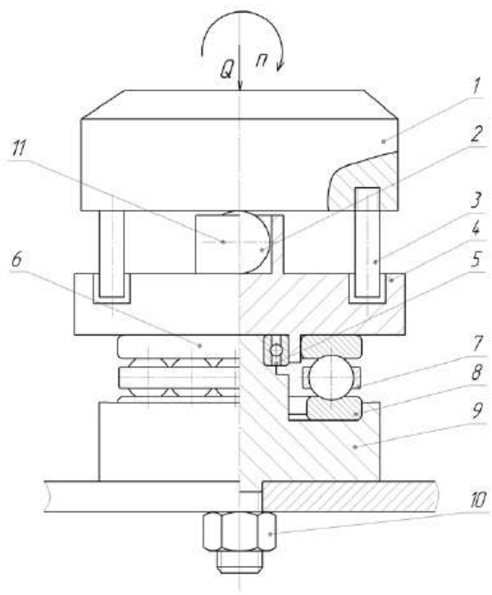

Fig. 2. Installation test machine for rolling bearings

Carrier 1 transmits rotation with frequency n through pins 3 to the upper disk 4 of the working head. The load Q on the bearing assembly is transmitted through ball 2. Ball 3 is fixed in a cylindrical cage 11. A radial bearing 5 is needed to center the upper disc and the lower head housing 9. A thrust ball bearing is tested, consisting of an upper ring 6, a lower ring 8 and a cage 7. The working head is attached to the table of the test bench with a nut 10. During wear tests, the test specimen is installed in place of the lower ring of the thrust bearing. When testing for slippage when the upper ring rotates at a speed n_1, the separator 7 is simultaneously rotated at a speed n_c.

The number of revolutions of the ring and cage was measured using a DT2234B electronic digital tachometer. Foil pieces 5 × 10 mm in size were attached to the upper ring and to the separator. The beam from the tachometer periodically hits the foil and records the number of revolutions per minute accurate to the first decimal place. The measurement results are shown in Tables 1 and 2.

Slip tests were carried out at loads Q = 100; 250; 500 N for bearing 8204. The revolutions of the upper ring were set in steps: n_1 = 250; 500; 1350 rpm.

The theoretical speed of rotation of the separator was calculated by the formula (9), the amount of slippage was determined by the formula (12). Slip tests were carried out under two lubrication modes: in the absence of lubrication and lubrication with Fiol-3 grease. The results of measurements and calculations are shown in Tables 1 and 2.

Table 1

Test results without lubrication

Speed, rpm	Q, N						n_0, rpm
	100	S_c	250	S_c	500	S_c	
n_1	250.2	0.0312	250.9	0.0322	250.4	0.0309	250
n_c	129.1		129.6		129.2		
n_1	497.4	0.0293	496.6	0.0312	495.9	0.0315	500
n_c	256.2		256.3		256.0		
n_1	1350	0.0321	1349	0.0320	1348	0.0317	1,350
n_c	697.4		696.8		696.1		

Table 2

Test results with Fiol-3 grease

Speed, rpm	Q, N						n_0, rpm
	100	S_c	250	S_c	500	S_c	
n_1	251.0	0.0331	250.5	0.0342	250.8	0.0350	250
n_c	129.8		129.7		129.9		
n_1	499.4	0.0323	498.5	0.0343	497.9	0.0335	500
n_c	258.0		258.1		257.6		
n_1	1351	0.0352	1349	0.0343	1349	0.0362	1,350
n_c	700.1		698.5		699.8		

Analysis of the results obtained shows that the slip coefficient is practically independent of the load and rotation speed. Slip fluctuations due to these factors are rather random. Average value of the slip coefficient for bearing 8204 without lubrication $S_c = 0,0313$, and when lubricated with Fiol-3 grease $S_c = 0,0342$. Thus, the use of lubricant increases slip by 8%.

Modeling rolling bearing wear

The calculation of wear is based on the mechanics of the contact interaction of a ball and a plane with wear. The sliding of a ball on a ring (Fig. 3) under a load Q is considered.

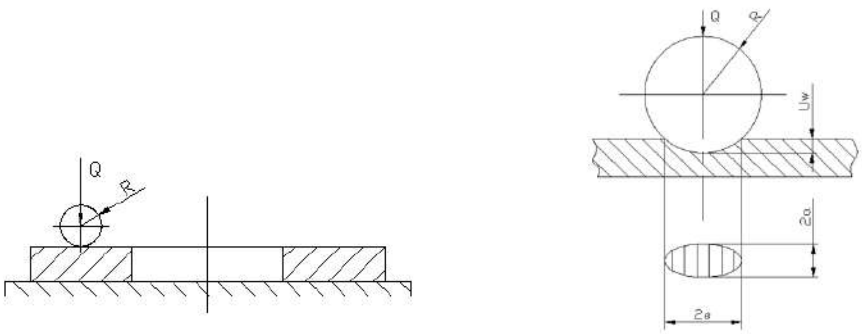

Fig. 3. Scheme of wear tests

The ring is stationary, the surface of the ring wears out. During the wear process, a groove with a width of *2b* is formed, which increases with wear. We assume that the ball does not wear out.

Ring wear model in differential form:

$$\frac{dU_w}{ds} = k_w \left(\frac{\sigma}{HB} \right)^m \left(\frac{\upsilon R}{\nu} \right); \tag{14}$$

or in the form:

$$\frac{dU_w}{ds} = k_w \sigma^m \Pi \,, \quad \Pi = (HB)^{-m} \left(\frac{\upsilon R}{\nu} \right),$$

where σ is the contact pressure;
Kw, m are the parameters of the wear model;
Uw is wear;
s is the friction path for ring.
HB is Brinell ring material hardness инелю;
υ is the relative sliding speed;
R is the radius of the ball;
ν kinematic viscosity of the lubricant.

In the process of wear, a platform is formed with dimensions: *2a* along the friction path and *2b* across the friction path. We assume that the contact pressure is evenly distributed over the contact area:

$$\sigma = \frac{Q}{\pi ab}. \tag{15}$$

The depth of the wear groove *Uw* is related to the width of the groove and the radius of the ball in the ratio:

$$U_w = \frac{b^2(s)}{2R}. \tag{16}$$

The friction path s for ring points is related to the size of the contact area in the sliding direction by the ratio:

$$s = 2azntS_c, \tag{17}$$

where *z* is the number of balls passing through the contact area, per revolution;
n is the number of revolutions per minute;;
t is the duration of the bearing;
Sc is the slip value.

The size a of the contact area can be determined by the Hertz formula:

$$a = 1{,}09\sqrt[3]{\left(\frac{QR}{E} \right)}, \tag{18}$$

where E is the modulus of elasticity of the ring material.

The main assumption is that the size of the contact area in the direction of motion of the ball is taken to be equal to the initial size a according to (18).

Differentiating equation (16) and substituting in (14) after transformations, we obtain the differential equation of the problem:

$$\frac{Q}{\pi ab} = \left(\frac{b}{\Pi k_w R}\frac{db}{ds}\right)\frac{1}{m}. \qquad (19)$$

The solution of the differential equation (20) with a zero initial area $b = 0$ gives an expression for determining the size of the wear area of the bearing ring b *(s)*:

$$b = \left((m+2)\left(\frac{Q}{\pi a}\right)^m \Pi k_w RS\right)^{\frac{1}{m+2}}. \qquad (20)$$

The inverse problem consists in determining the parameters of the bearing ring wear model Kw and m for the function b *(s)* known from the experiment. Based on the test results, this function can be represented as a power-law approximation:

$$b(s) = cs^{\beta}. \qquad (21)$$

Then equation (20) can be represented in the form:

$$\frac{c^{m+2}S^{\beta m+2\beta}}{(m+2)} = \left(\frac{Q}{\pi a}\right)^m \Pi k_w RS. \qquad (22)$$

From the condition that this equation is satisfied, we obtain:

$$\beta m + 2\beta = 1. \qquad (23)$$

or

$$m = \frac{1-2\beta}{\beta}; \qquad (24)$$

Taking into account (23), from (22) it follows:

$$k_w = \frac{c^{m+2}}{(m+2)}\left(\frac{\pi a}{Q}\right)^m \Pi R, \qquad (25)$$

Thus, a generalized solution of the contact problem of the interaction of a ball and a bearing ring during ring wear is proposed. At the same time, an approximate solution of the problem of ring wear by a ball is carried out under the assumption of a slight change in the size of the contact area in the direction of the ball movement.

Conclusions

1. The main bearing unit of modern machines is rolling bearings. There are practically no methods for calculating and testing bearings for wear, which complicates their design.
2. A computational and experimental method for determining the amount of slippage in ball bearings is proposed. From the kinematics of bearings, relations for the movements of balls and rings without slipping are known; on the other hand, the number of revolutions of the separator can be measured experimentally. The difference between the calculated and actual numbers of revolutions of the separator allows you to determine the amount of slip.
3. Analysis of the results obtained shows that the slip coefficient does not depend on the load and rotation speed. Slip fluctuations due to these factors are random. The use of lubricant increases slip by 8%.

4. The solution of the wear contact problem for the ball and bearing ring in case of wear of the ring has been carried out. An approximate solution of the problem of ring wear by a ball is carried out under the assumption that the contact area remains unchanged in the direction of the ball movement.

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Диха О. В., Дитинюк В.О., Диха М.О. Дослідження проковзування та зношування в опорах кочення машин

Метою роботи було дослідження процесів проковзування і зношування в підшипниках ковзання машин. Визначено, що проковзування в підшипниках є головною причиною виходу деталей підшипника з ладу за критерієм зносу. Представлено аналітичні співвідношення для визначення величини проковзування та шляху ковзання в підшипнику. Для експериментального дослідження проковзування в підшипниках кочення спроектована випробувальна установка. Проведені експериментальні випробування по впливу на проковзуванння навантаження, швидкості ковзання та умов змащування у підшипнику. Запропонована модель зношування кілець підшипника ковзання на основі розв`язку зносоконактної задачі. Отримані формули для розрахунку зносу та параметрів моделі зношування. Отримані результати рекомендовані для оцінки впливу конструктивних і технологічних факторів на довговічність підшипників кочення за критерієм зносу.

Ключові слова: підшипники кочення, проковзування, експериментальна установка, умови змащування, модель зношування, зносоконтактна задача