DOI: 10.31891/2079-1372

THE INTERNATIONAL SCIENTIFIC JOURNAL

PROBLEMS OF TRIBOLOGY

Volume 28 No 2/108-2023

МІЖНАРОДНИЙ НАУКОВИЙ ЖУРНАЛ

ПРОБЛЕМИ ТРИБОЛОГІЇ

PROBLEMS OF TRIBOLOGY

INTERNATIONAL SCIENTIFIC JOURNAL

Published since 1996, four time a year

Volume 28 No 2/108-2023

Establishers:

Khmelnitskiy National University (Ukraine)
Lublin University of Technology (Poland)

Associated establisher:
Vytautas Magnus University (Lithuania)

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

Indexed: CrossRef, DOAJ, Ulrichsweb, Google Scholar, Index Copernicus

E-mail: tribology@khmnu.edu.ua

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

ПРОБЛЕМИ ТРИБОЛОГІЇ

МІЖНАРОДНИЙ НАУКОВИЙ ЖУРНАЛ

Видається з 1996 р. ***Виходить 4 рази на рік***

Том 28 **№ 2/108-2023**

Співзасновники:
Хмельницький національний університет (Україна)
Університет Люблінська Політехніка (Польща)

Асоційований співзасновник:

Університет Вітовта Великого (Литва)

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

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

Зареєстровано Міністерством юстиції України
Свідоцтво про держреєстрацію друкованого ЗМІ: Серія КВ № 1917 від 14.03. 1996 р.
(перереєстрація № 24271-14111ПР від 22.10.2019 року)

Входить до переліку наукових фахових видань України
(Наказ Міністерства освіти і науки України № 612/07.05.19. Категорія Б.)

Індексується в МНБ: CrossRef, DOAJ, Ulrichsweb, Google Scholar, Index Copernicus

Рекомендовано до друку рішенням вченої ради ХНУ, протокол № 15 від 25.05.2023 р.

***Problems of Tribology**, V. 28, No 2/108-2023*

Problems of Tribology

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

CONTENTS

Problems of Tribology, V. 28, No 2/108-2023

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

ЗМІСТ

Problems of Tribology, *V. 28, No 2/108-2023, 6-14*

Problems of Tribology

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

E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-6-14

Wear Resistance Research and Its 2-factor Modeling of Nanoscaled Silicon Carbide Detonation Coatings

A.H. Dovhal*, L.B. Pryimak, V.V. Varijukhno

National Aviation University, Ukraine

**E-mail: andrii.dovhal@npp.nau.edu.ua*

Received: 30 March 2023: Revised: 10 April 2023: Accept:14 April 2023

Abstract

This research is related to the spheres of wearproof coating testing. The SiC coating has been deposited on the medium carbon steel using detonation deposition using the magnet coil flux of back direction. It has been established that only nanoscaled particles are deposited on the surface which had been accumulated in aggregates of different shape. The structure of the obtained coating has been thoroughly researched on the electronic microscope in previous publication. The obtained coating has been developed for testing on the friction bench modeling the friction process that is taking place in the couple of main and rod journals of internal combustion engines. The coating has also the corrosion protection properties. The nanoscaled coating on mild carbon steel had been tested under specified conditions and their friction surfaces had been researched on electronic microscope with the view of determination of wear mechanism. The two-factor modeling of the wear rate and friction factor has been done and three-dimensional diagrams have been plotted and analyzed.

Key words: wear, wear rate, friction factor, nanoscaled coating, detonation coating deposition, magnet modified deposition

Introduction

The lifetime of the internal combustion engine elements can be improved by wearproof coatings deposited by different methods. The main component of coating suggested is the silicon carbide SiC and as the bond for it the alumina has been selected. Having the good hardness all these elements are of well abrasive properties, but not in small gain sizes. If the granularity of these abrasives is no bigger than 5 micrometers they did not wear the steel surfaces owing two features. The first one is too small size of particles makes the smallest scratches on surface resulting in so-called surface polishing to mirror roughness grade. The second one this dimension of particles "fills" the generic steel roughness cavities thus increasing the friction contact area and reducing the contact pressure. So, the abrasive particles sized less than 5 micrometers is not "wear abrasive" that increases the wear, but it is "run-in abrasive" that decreases the wear of steel surface. It has been proven several times using the compact fine grain material made of silicon carbide and alumina when mixed and milled up to less than 5 micrometer granularity and avoiding recrystallization processes during the material synthesis as well as the same fine grained coating on the steel surface. Recently, the nanoscaled coating (100 micrometers thick) had been acquired [3] and its structure has been investigated. This study is devoted to tribotechnical investigation of these coatings, establishing the wear mechanisms and results modeling.

Review of the latest research

Formerly [1], the specific way acquired batch mixture of $SiC-Al_2O_3$ (which was milled in steel vessels by steel milling bodies in 32 hours up to 2,1 micrometers average particle granularity) content, which had the iron millings in the batch mixture charge, was used for acquisition of wearproof coating deposition by detonation method modified by magnetic field. So it had been established on direct polarity of coil magnet the microparticles of silicon carbide and alumina had been deposited on the substrate. The coating had demonstrated not only high wear resistance 40-55 micrometers/km and friction factor 0,42-0.45 [1], but also high wear resistance at elevated temperatures up to 500°C it makes 40-55 micrometers/km and friction factor 0,32-0.34 [2] due to formation of the glass-like superficial structures reducing the wear rate and friction factor comparing with the 250°C.

Using the gas detonation deposition from the batch mixture which contains the silicon carbide and aluminum oxide particles, with the steel millings which have a size from 250-400 nanometers, on the direct polarity the fine grained microstructure is acquired and on the reverse polarity of the magnet coil the nanostructure the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers had been acquired [3] and its structure had been thoroughly researched. The present paper is devoted to research the tribotechnical descriptions of these coatings.

Scientific interest to silicon carbide coatings is growing throughout the world.

So, in article [4] researchers had investigated the laser-prepared SiC nanocoating: preparation, properties and high-temperature oxidation performance. The SiC nanocoatings were prepared on graphite substrates via a laser treatment process. A high-temperature oxidation test was also conducted to determine their antioxidation performance. The results show that laser irradiation triggers the transformation from micro SiC particles into SiC nanocoating consisting of numerous polycrystalline SiC nanoparticles. At the laser energy density of 10.42 kJ/cm^2, the prepared SiC nanocoating reveals the best oxidation resistance at a high-temperature environment in tested samples [4].

Scientists publishing paper [5] have been studying silicon carbide coatings produced at different deposition conditions with use of high temperature nanoindentation. So, The elastic modulus and hardness of different silicon carbide (SiC) coatings in tristructural-isotropic fuel particles were measured by in situ high temperature nanoindentation up to 500 °C. Three samples fabricated by different research institutions were compared. Due to varied fabrication parameters the samples exhibited different grain sizes and one contained some visible porosity. However, irrespective of the microstructural features in each case the hardness was found to be very similar in the three coatings around 35 GPa at room temperature. The elastic modulus differed for the three tristructural-isotropic coatings with room temperature values ranging from 340 to 400 GPa [5].

The research [6] signifies an attempt to apply composite coating by co-deposition coating and assessing, enhancement the Nickel coatings features, by adding the particles of silicon-carbide to solution of electrodeposited. Stainless steel specimens have been subject to electroplating coating utilizing Nickel and Nano silicon carbide particles (70-100 nm) with various amounts (16, 24, 32 and 40) g/L. After coating, the specimens were tested by SEM, AFM, impeded in a solution with 3.5 percent NaCl to investigate the corrosion performance. Then testing the microhardness, and wear resistance. Results obtained from this work showed a great reduction in corrosion currents caused by adding of inert nanoparticles. These enhancements had been detected on all conducted tests for corrosion and wear.

So, in article [7] researchers had investigated the strengthening and thermal stabilization of polyurethane nanocomposites with silicon carbide nanoparticles by a surface-initiated-polymerization approach. Silicon carbide reinforced polyurethane nanocomposites were fabricated by a facile surface-initiated-polymerization (SIP) method. The particle loading was tuned to up to 35 wt% without any obvious shrinkage and breakage as compared with the conventional direct mixing method. An increased thermal stability of the composites was observed with the addition of the silicon carbide nanoparticles under thermo-gravimetric analysis (TGA). Tensile strength was observed to increase dramatically with the increase of the particle loading. Both the uniform particle dispersion and the strong chemical bonding between the nanoparticles and the polymer–matrix contributed to the enhanced thermal stability and improved mechanical properties.

Scientists publishing paper [8] have been studying the compacting of silicon carbide nanopowder in high-pressure device. The nanopowders of silicon carbide were sintered under the pressure from 3,5 GPa and under the temperatures 1600-1800 °C. So the obtained materials had the following properties: density - 3,07-3,20 g/cm^3; microhardness – 15-30 GPa; porosity – 1,2-4,4 and weight wear rate – 0,0061-0,0462 g/cm^2. On the SEM images the big grain growth had been noticed.

The research [9] is about the synthesis of silicon carbide nanoparticles exhibiting monolayer to few-layer graphene coatings and characterizes their optical response to confirm their plasmonic behavior. A multistep, low temperature plasma process is used to nucleate silicon particles, carbonize them in-flight to give small silicon carbide nanocrystals, and coat them in-flight with a graphene shell. These particles show surface plasmon resonance in the infrared region. Tuning of the plasma parameters allows control over the nanoparticle size and consequently over the absorption peak position. A simplified equivalent dielectric permittivity model shows excellent agreement with the experimental data. In addition, optical characterization at high temperatures confirms the stability of their optical properties, making this material attractive for a broad range of applications.

In the paper [10] researchers have discovered the development and characterization of silicon carbide coating on graphite substrate. The development of materials with unique and improved properties using low cost processes is essential to increase performance and reduce cost of the solid rocket motors. Specifically, advancements are needed for boost phase nozzle. As these motors operate at very high pressure and temperatures, the nozzle must survive high thermal stresses with minimal erosion to maintain performance. Currently three material choices are being exploited; which are refractory metals, graphite and carbon-carbon composites. Of these three materials graphite is the most attractive choice because of its low cost, light weight, and easy forming. However, graphite is prone to erosion, both chemical and mechanical, which may affect the ballistic conditions and mechanical properties of the nozzle. To minimize this erosion Pyrolytic Graphite (PG) coating inside the nozzle is used. However, PG coating is prone to cracking and spallation along with very cumbersome deposition process. Another possible methodology to avoid this erosion is to convert the inside surface of the rocket nozzle to Silicon Carbide (SiC), which is very erosion resistant and have much better thermal stability compared to graphite and even PG. Due to its functionally gradient nature such a layer will be very adherent and resistant to spallation. Despite its very good adhesion due to its functionally gradient nature, this layer due to its porous nature exhibit poor oxidation performance compared to a dense SiC layer. The research [10] is focused on synthesizing, characterizing and oxidation testing of a bi-layer; a functionally gradient inner layer and dense outer layer, SiC coating on graphite.

In the article [11] researchers had investigated the fabrication of silicon carbide (SiC) coatings from pyrolysis of polycarbosilane/aluminum. So, the SiC coatings were fabricated by the pyrolysis of polycarbosilane (PCS)/aluminum, in which PCS acts as preceramic precursor of SiC and aluminum (Al) powder acts as an active filler to both compensate the volume shrinkage of SiC coatings during pyrolysis and enhance the adhesion of SiC coatings with Ferroalloy substrate. SiC coatings as thick as ~35 lm without cracking can be fabricated through our approach. Microstructural analysis revealed that the SiC coatings were composed of α-Al2O3 and β-SiC. Hardness and modulus of the SiC coatings as measured by nano-indentation were 12.2 ± 4.0 and 153.7 ± 47.0 GPa, respectively

Scientists publishing paper [12] have been studying high-performance Ni-SiC coatings fabricated by flash heating. In this research, a novel flash heating coating application technique was utilized to create Ni-SiC coatings on carbon steel substrates with SiC contents much higher than is achievable using certain conventional coating techniques. Hardness profiles showed that the coatings improved the substrate by as much as 121%, without affecting the substrate. Tribotests showed that the wear performance was improved by as much as 4.7 times in terms of the wear rate ($mm^3/N*m$) for the same coating when using an Al_2O_3 counterpart. Pure SiC coatings as a reference were also fabricated. However, the SiC coatings experienced elemental diffusion of Fe from the carbon steel substrate into the coating during fabrication. This occurred due to the increased heat input required for pure SiC to fuse to the substrate compared to the Ni-SiC coatings and resulted in decreased tribological performance. Diffusion of Fe into the coating weakened the coating's hardness and reduced the resistance to wear. It was concluded that ceramic–metallic composite coatings can successfully be fabricated utilizing this novel flash heating technique to improve the wear resistance of ceramic counterparts.

The research [13] is about the wear characterization and microstructure evaluation of silicon carbide based nano composite coating using plasma spraying. So there thin films of various thickness of SiC – Al_20_3 composite is deposited on aluminum alloy 6061 using Plasma spraying process. Wear tests on pin-on-disc tester is conducted to compare the wear characteristics of uncoated and coated samples. The micro hardness tests of coated samples and uncoated samples are compared. The microstructure characterization of the Nano-coated films using Scanning Electron Microscope (SEM) of the samples is studied. The results and studies clearly depicts that the major variations in coating performance can be obtained by exploiting proper plasma spray conditions and optimum percentage of SiC – Al_20_3 in composite coatings.

In the paper [14] researchers have discovered the tribological behavior of thermally sprayed silicon carbide coatings. SiC coatings have been successfully deposited using thermal spray detonation technique with a newly patented feedstock. Their tribological performance was compared to bulk SiC for dry and lubricated conditions (polyalphaolefin and 3.5 wt% NaCl solution).The lowest coefficient of friction (CoF=0.10) and wear-rate were detected with polyalphaolefin lubricant regardless of the test pair due to mixed fluid film lubrication. Contradicting results were recorded under other test conditions. The coatings show low CoF of 0.20 in comparison to four times higher CoF of bulk SiC under dry sliding. Oppositely, SiC coatings in NaCl solution record five times higher CoF compared to bulk SiC CoF of 0.20. Such behavior is associated with tribochemical reaction and tribo-corrosion mechanisms occurring in dry and NaCl sliding, respectively.

Scientists publishing paper [15] have been studying the properties features of nanostructured silicon carbide films and coatings, acquired by new method. There the new method of nanostructured silicon carbide films and coatings acquisition, which structure can be changed depending on the application industry, had been developed. Acquired films and coatings are suitable for use in metallurgy, nuclear power industry, microelectronics and in high-temperature stoves. The nanostructures coatings were acquired from the silicon vapors and gaseous carbon under high temperatures, and changing the supply speed, pressure and temperature the grains sizes of silicon carbide in coating can also be changed. Some improved properties of acquired coatings had been revealed.

So, as it can be already seen, the great worldwide interest to silicon carbide coatings in different application areas is continuously growing and any research is worthy to promote the scientific progress.

Research aim

Scientific development of nanoscaled composition coatings for crank shaft journal of internal combustion engines.

Originating from the aim of article paper the following tasks of research were preset:

1. Simulating the friction conditions similar to crank shaft journals of internal combustion engine without lubricant.
2. Nanoscaled coatings wear testing and their friction surfaces research.
3. Modeling the wear rate and friction factor of the nanoscaled silicon carbide coatings in the preset ranges of factors.

Research methodology

For study of interactions between properties of coatings with their phase composition and structure, and also an external factors influence the choice of research methods has the great importance. The receiving of reliable results of research in this work is provided by modern equipment and devices, approved methodologies, necessary productivity of experiments, by careful treatment of specimens before and after the experiment, strict adherence of order of experiment.

For receiving a charge of silicon carbide ceramics with aluminum oxide admixtures, the starting powders were used: silicon carbide grade 64C (ГОСТ 26 327-84) with an average size of 45-55 μm, aluminum oxide (ТУ 6-09-03-350-73) with particles of average size 45 -50 microns.

The chemical content of the initial powders and possible admixtures is given in Table 1.

Table 1

Results of analysis of initial powders in masses. %

Powder name	Al	Si	Mg	Fe	Ni	Cr	Ti	Ca	Zr	Ag	Cu
SiC	10^{-3}	maj.	10^{-4}	10^{-3}	-	-	-	10^{-4}	-	-	-
Al_2O_3	maj.	-	10^{-3}	>0,1	>1	0,01	-	-	-	10^{-4}	10^{-3}

The common procedure for the formation of composite materials from the initial powders is their mutual mixing and grinding.

For acquisition of SiC-based coating the batch mixture charge with 50% Al_2O_3 additive, and the powders components in the appropriate proportions were mixed with simultaneously grinded for 32 hours in the laboratory planetary mill Sand-1 in an alcohol (ethanol) medium in order to avoid particles agglutination.

In this case, the table rotational speed was 648 rpm, the drum vessels rotation speed was 1620 rpm throughout 32 hours. To prepare the charge, the steel vessels of 340 cm^3 volume and steel grinding bodies (balls) made of steel of ШХ15 with a diameter of 10-15 mm were used.

The ratio of the batch mixture charge mass to the grinding bodies (balls) mass is 1: 3. After grinding, the batch mixture charge was dried and sifted to avoid lumps and clods. The granulometric composition of the resulting mixtures after milling was determined in aqueous media on a laser microanalyzer "SK Lazer Micron Sizer PRO 7000" and average particle size makes about 2,1 micrometers. Content and size of nanoscaled particles have not been determined in any technique.

Coatings in the work were deposited by the detonation method on the installation “Dnepr-3M” detonation-gas installation is intended for coating made of metal powders, hard alloys, ceramics and composite materials on the surfaces of machine parts, devices, apparatuses and tools during their manufacture, as well as reconditioning. On the barrel of detonation installation the magnet coil of the reverse polarity current was fed in it. Thus the iron millings had retardated the microsized particles, but not nanosized. The coating thickness varied about 60 micrometers after about 120 shots of detonation installation barrel (so approximately 0,5 micrometer per shot) [3] comparing with the microstructural coating 200 micrometers per 30 shots (so approximately 5 micrometer per shot) [1-2]. So the about 90% of batch mixture charge was wasted, what allows making the conclusion the amount of nanosized particles was about ~10% (overwhelming majority of nanoscaled particles is SiC) The content of the nanoparticles is about 85% of SiC, 10% of Al_2O_3 and 5% of Fe_2C. No metallic particles were detected in the coating content. Coating thickness was about 50-60 micrometers. Within the 40 000 electronic zoom [3] the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers are acquired

For research of structure and phase composition of the structure and phase content of coating on the basis (SiC-Al_2O_3), and also their friction surfaces was conducted by SEM microscopy and micro X-ray spectral analyses, X-ray-phase (ДРОН-2.0 in $Cu_{k\alpha}$ -radiation).

Composite coatings (charge of SiC-Al_2O_3 after 32 hours milling deposited by detonation through the reverse magnet) were testes on the friction test machine MT-89 of Institute for Problems of Materials Science under the loads from 0.2 to 15 MPa and under the friction speeds from 0.2 to 20 m/sec. Friction layout is “pin-on-shaft” without lubricants. The coating has been deposited on the pin surface.

Research results and discussion

Modeling of the wear resistance process of the composition coatings for crankshaft journal of internal combustion engines has demonstrated the following results. The range of factors was divided on the three levels of change (table.2.)

Table 2

Conditions of research of wear resistance of nanocomposite coatings in conditions of high load wear

Factors	Load X_1, P, [MPa]	Speed X_2, V, [m/s]
Top level (+1)	15	20
Lower level (-1)	0,2	0,2
Basic level (0)	7,5	10
Variable interval (J)	7,5	10

The experimental results of wear rate (micrometers/kilometer) and friction factor (unitless) were recorded to relevant factors in the model matrix (table 3.)

Table 3

Central noncomposite rotatable matrix of the 2nd order for number of factors K = 2

№ of experiment	Factors						Experimental data on proper factor level		Model-estimated data on proper factor level	
	X_0	X_1	X_2	X_1X_2	X_1^2	X_2^2	Y_1	Y_2	Y_1	Y_2
1	1	1	1	1	1	1	14,1	0,25	48,29	0,40
2	1	1	-1	-1	1	1	0,9	0,19	2,73	0,20
3	1	-1	1	-1	1	1	19,3	0,31	57,73	0,57
4	1	-1	-1	1	1	1	1,3	0,24	9,29	0,37
5	1	1	0	0	1	0	10,1	0,22	24,20	0,23
6	1	0	1	0	0	1	16,8	0,28	50,11	0,42
7	1	-1	0	0	1	0	12,5	0,28	32,20	0,40
8	1	0	-1	0	0	1	1	0,21	3,11	0,22
9	1	0	0	0	0	0	10,3	0,25	10,30	0,25

Response function of experimental data for modeling: Y_1 is linear wear rate (I, μm/km). Y_2 is a friction factor.

The function of response in the factor space has the mathematic expression: $Y = B_0 + B_1X_1 + B_2X_2 + B_{12}X_1X_2 + B_{11}X_1^2 + B_{22}X_2^2$

Finally, when the coefficients B were calculated and after their statistical significance check. the models, obtained after rotatable planning of the second power order, have the mathematic expression:

For wear rate Y_1 (fig 1.): $Y_1=10,3-4X1+23,5X_2-0,72X_1X_2+2,896X_1^2+1,312X_2^2$.

For friction factor Y_2 (fig 2.): $Y_2=0,25-0,085X1+0,1X_2-0,0015X_1X_2+0,0697X_1^2+0,0664X_2^2$.

According to the data, two-dimensional graphic dependencies were plotted (fig. 1. and 2.). Thus, an analysis of the effect of all two factors both the load and friction speed to wear rate and friction factor are held.

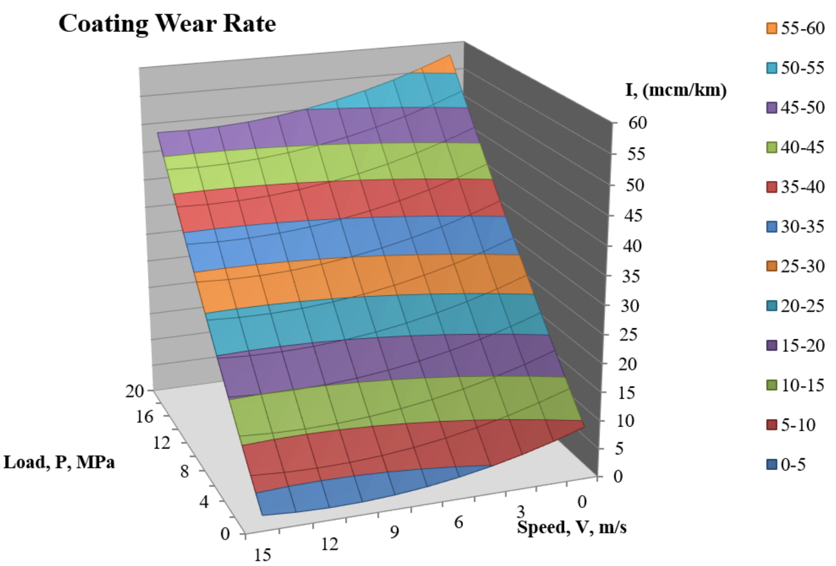


Fig. 1. Diagram of wear rate modeling of nanoscaled coating from friction speed and contact load

The developed model allows to comprehensively and visually estimating the influence of factors on the desired function of the response, to carry out optimization measures and mathematical processing of regression dependence, like a derivation and the precise optimum detection.

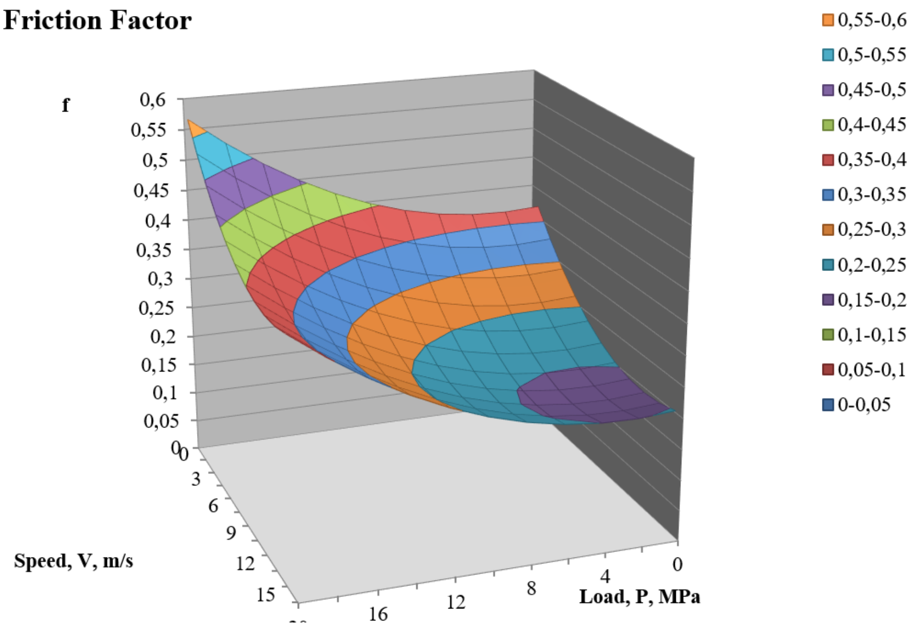
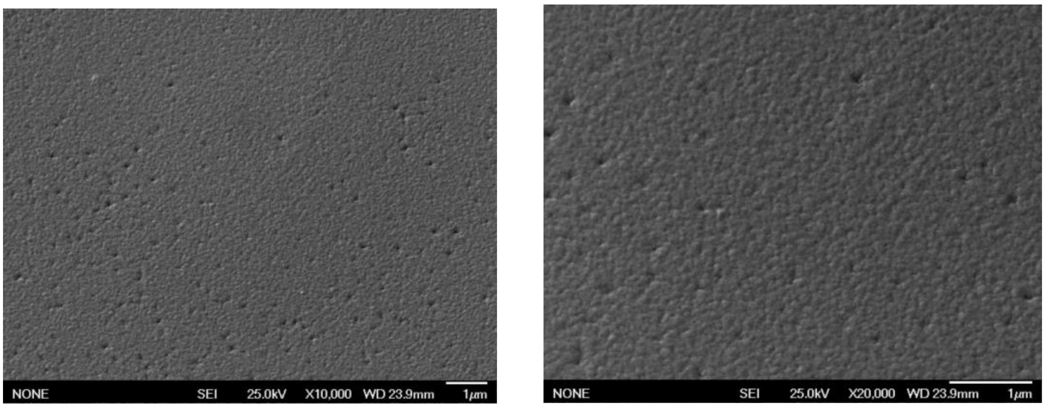


Fig. 2. Diagram of friction factor modeling of nanoscaled coating from friction speed and contact load.

The optimum friction modes of the nanoscaled particles coating is the following. The minimal wear of the coating is 2,18 micrometers per kilometer path under the modes: speed 12,5 m/s and load 0,2 MPa, and the minimal friction factor is 0,188536 for the load 12,5 m/s and load 17,5 MPa. It is about sparing run-in process, but the working modes of the coating 20 MPs and 15 m/s the wear rate of the coating will be 48,288 micrometers per kilometer and the friction factor will be 0.3996. Totally the nanoscaled coating will work in the antifriction mode so as the friction factor will be less than 0,4.

Wear mechanisms of the nanoscaled coatings for crankshaft journal of internal combustion engine were researched using the scanning electronic microscopy (SEM) images.

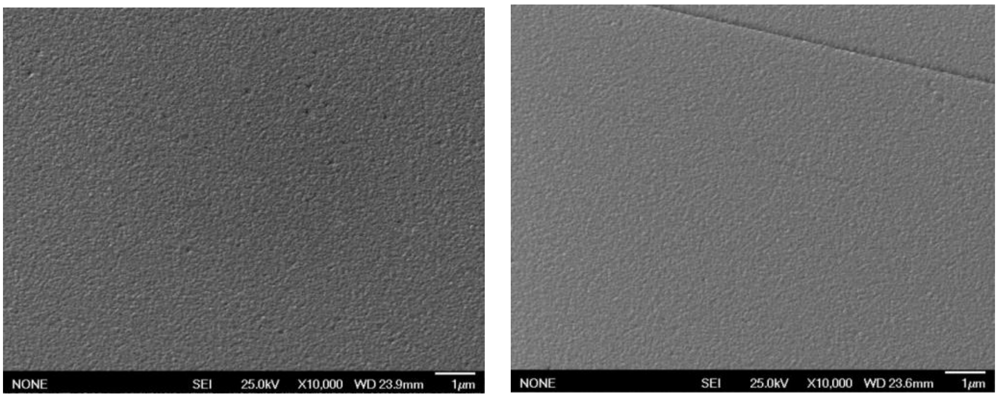
The tests were carried out at sliding speeds of 0,2-15 m/s and loads of 0,2-25 MPa, which simulates the work of the contact area of the “crank shaft journal-insert” elements of medium load intensity. As a counterbody: steel X16H4 (HRC 60-64) was used, since it is the material of the ICE crank shaft journal inserts. For the explanation of the results of the friction and detection of wear mechanism let’s consider the friction surfaces of the coating investigated on the microscope. For the convenience of comparison let’s consider the initial surfaces (fig. 3.). So the initial view of the friction surfaces are about the presence of even, uniform and similar grain structure under the 10000 and 20000 electron zoom (excepting some pits between the elements of the structure).



a) b)

Fig. 3. SEM-images of the Initial Surfaces of the Nanoscaled Detonation Coatings: a) 10 000 zoom; b) 20 000 zoom.

After application of small loads the compacting of the friction surface is observed unlike a rough surface of initial surfaces [3]. And even creation of the some friction lines are detected on the friction surfaces those are not detected under the light optical observation under the magnifying lens (fig. 4.).

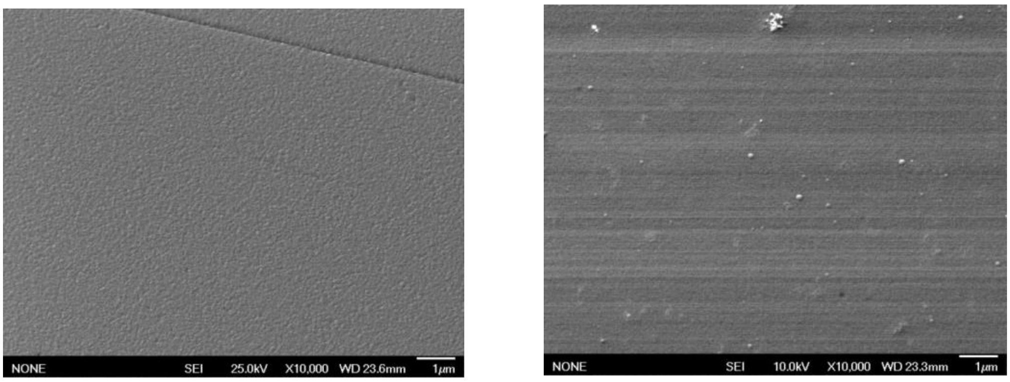


a) b)

Fig. 4. SEM-images of the Friction Surfaces of the Nanoscaled Detonation Coatings under the 0,2 MPa load (15 m/s) 10 000 zoom: a) 1 stripe area; b) 2 stripe area.

So the analysis of the fig. 4. is about the formation of the compact friction surface and even some friction lines are seen on the surface. So as the surface roughness was satisfactorily, the single wear stripes were created due to formation of the big wear products and those are scaring the surface deeply. Son under the smallest friction load the compaction of the friction surface was noticed and surfaces do not have the pores and cavities the initial surfaces have.

When increasing the load to 20 MPa on the friction bench MT-89 on the scanning microscope images (fig. 5.) the even uniform wear was detected of value 19,3 micrometer per kilometer. So well friction stripes were observed on the friction surfaces. The wear process was liked a burn out from the MT-89 test specimens.



a) b)

Fig. 5. SEM-images of Sliding Friction Surfaces of the Coatings Developed (10 000 zoom): a) under 0,2 MPa load; b) under 20 MPa load

The chemical content made by microscope X-ray analyzer of the top surface layer was of the following oxides: SiO_2, Al_2O_3, FeO and Fe_2O_3 and pure iron was detected as well, what was proven by X-ray phase analysis. So the wear mechanism is close to oxidative one.

Conclusions

Using the gas detonation deposition from the batch mixture which contains the silicon carbide and aluminum oxide particles, which have particle of iron sized from 250-400 nm, on the direct polarity the fine grained microstructure is acquired and on the reverse polarity the nanostructure the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers [3] had been acquired.

Under the friction modes the nanoscaled particles coating compacting and formation of an integral protection layer had been detected using the scanning electron microscopy and low wear rate and friction factors were detected and acquired.

As a result of the mathematical modeling of the experimental data obtained by the polynomial regression dependence of the 2nd order for 2 factors, taking into account all experimental data, it was established the optimum for these coatings use. The optimum friction modes of the nanoscaled particles coating is the following. The minimal wear of the coating is 2,18 micrometers per kilometer path under the modes: speed 12,5 m/s and load 0,2 MPa, and the minimal friction factor is 0,188536 for the load 12,5 m/s and load 17,5 MPa. It is about sparing run-in process, but the working modes of the coating 20 MPs and 15 m/s the wear rate of the coating will be 48,288 micrometers per kilometer and the friction factor will be 0.3996. Totally the nanoscaled coating will work in the antifriction mode so as the friction factor will be less than 0,4.

References

1. A. Dovgal, L. Pryimak, I. Trofimov A Modified Method of Applying Detonation-Sprayed Composite Coatings by a Magnetic Field.// Eastern-European Journal of Enterprise Technologies.– Volume 6/5 (84). – 2016. – P. 33-38.

2. L. Pryimak, A. Dovgal, Ye. Puhachevska Analysis of Structure and Tribotechnic Properties of Plasma Carbide-Silicon Coatings Under Conditions of Elevated Temperatures // Eastern-European Journal of Enterprise Technologies. – Volume 1/5 (85). – 2017. – P. 46-53.

3. A.H. Dovhal*, L.B. Pryimak Structure research of nanoscaled silicon carbide detonation coatings of tribotechnical application, Problems of Tribology, V. 27, No 1/103-2022, P. 26-33.

4. XiaodongHu, Rongjie Jiang, Fang Luo, Yuanhang Lu, Yuxin Wang and Zhen He The laser-prepared SiC nanocoating: preparation, properties and high-temperature oxidation performance. // Mater. Res. Express 8 (2021) 085003 pp. 1-12.

5. Nadia Rohbeck, Dimitrios Tsivoulas, Ian P. Shapiro, Ping Xiao, Steven Knol, Jean-Michel Escleine, Marc Perez, and Bing Liu Comparison study of silicon carbide coatings produced at different deposition conditions with use of high temperature nanoindentation // J Mater Sci (2017) 52: pp. 1868–1882.

6. Nawal Mohammed Dawood, Nabaa S. Radhi, Zainab S. Al-Khafaji Investigation Corosion and Wear Behaviour of Nickel Nano-Silicon Carbide on Stainless Steel 316L // Material Science Forum, Vol. 1002, 2020, pp. 33-43.

7. Zhanhu Guo, Ta Y. Kim, Kenny Lei, Tony Pereira, Jonathan G. Sugar, H. Thomas Hahn Strengthening and thermal stabilization of polyurethane nanocomposites with silicon carbide nanoparticles by a surface-initiated-polymerization approach // Composites Science and Technology N 68 (2008) pp. 164–170.

8. А. П. Гаршин, С. П. Богданов, В. А. Пономаренко Компактирование нанопорошка карбида кремния в аппарате высокого давления // Порошковая металлургия: Инженерия поверхности, новые порошковые композиционные материалы, сварка. Сборник докладов 9-го международного симпозиумаМинск, 8-10 апреля 2015 года. с. 288-297.

9. Devin Coleman and Lorenzo Mangolini Plasmonic Core−Shell Silicon Carbide−Graphene Nanoparticles // Material Science & Engineering Program and Mechanical Engineering Department, University of California, Riverside, Riverside, California 92521, United States, ACS Omega Press 2019, N 4, pp. 10089−10093.

10. F Z Mohammad, M Akhtar Sharif, M Anas Ahmed, Muhammad Suhail. Development and Characterization of Silicon Carbide Coating on Graphite Substrate. // J Chem Edu Res Prac, 2022, N 6 (2), pp. 258-266.

11. Daxiang Yang, Yuxi Yu, Xiaofeng Zhao, Yongcai Song, Eddie Lopez-Honorato, Ping Xiao, Delin Lai Fabrication of Silicon Carbide (SiC) Coatings from Pyrolysis of Polycarbosilane/Aluminum // J Inorg Organomet Polym (2011) N 21 pp:534–540.

12. Peter Renner, Ajinkya Raut and Hong Liang High-Performance Ni-SiC Coatings Fabricated by Flash Heating // Lubricants 2022, 10, 42 pp.1-20. https://doi.org/10.3390/lubricants10030042

13. S.M.Muneera, M.Nadeerab Wear characterization and microstructure evaluation of silicon carbide based nano composite coating using plasma spraying // Materials Today Proceedings Volume 5, Issue 11, Part 3, 2018, Pages 23834-23843.

14. F. Mubarok, N. Espallargas Tribological behaviour of thermally sprayed silicon carbide coatings // Tribology International, N 85 (2015) pp. 56–65.

15. К. Н. Филонов, В. Н. Курлов, Н. В. Классен, Е. А. Кудренко, Э. А. Штейнман Особенности свойств наноструктурированных карбидокремниевых пленок и покрытий, полученных новым способом. // Известия РАН. Серия физическая, 2009, том 73, № 10, с. 1457–1459.

А. Г. Довгаль, Л. Б. Приймак, В. В. Варюхно. Дослідження та двофакторне моделювання зносостійкості нанорозмірних карбідокремнієвих детонаційних покриттів

Це дослідження пов'язане з галузями, випробування зносостійких покриттів. SiC покриття наносилося детонаційним методом на середньовуглецеву сталь, використовуючи зворотній магнітний потік котушки. Встановлено, що тільки нанорозмірні частинки осаджуються на поверхні та накопичуються в агрегатах різної форми. Структура одержаного покриття цілком досліджена на електронному мікроскопі в попередній публікації. Одержане покриття розроблене для випробування на машині тертя, що моделює процес тертя, який має місце у корінних і шатунних шийках двигунів внутрішнього згоряння. Покриття має також властивості захисту від корозії. Нанорозмірне покриття на м'якій вуглецевій сталі, було випробувано згідно з конкретизованими умовами та їх поверхні тертя були досліджені на електронному мікроскопі з метою визначення механізму зношування. Було проведено двофакторне моделювання інтенсивності зношування і коефіцієнта тертя та були побудовані і проаналізований двовимірні графіки.

Ключові слова: знос, зносостійкість, коефіцієнт тертя, нанорозмірне покриття, детонаційне нанесення, магнітномодифіковане нанесення.ня, максимальні дотичні напруження, мікрогеометрія, тертя спокою.

Problems of Tribology, V. 28, No 2/108-2023, 15-19

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-15-19

Influence of lubricant material in the point contact zone of rolling friction on fatigue life for friction bearing units

A. Milanenko*, A. Savchuk, Y. Turitsa

National Transport University, Kyiv, Ukraine
E-mail: milanmasla@gmail.com

Received: 5 April 2023: Revised: 14 April 2023: Accept:5 May 2023

Abstract

A comprehensive methodology has been developed to assess the rheological and tribotechnical properties to establish the impact of the lubricant in dynamic lubrication conditions. The results of the research indirectly affect the fatigue life of bearing units under conditions of rolling friction.

Key words: Point contact zone, fatigue life, bearing units, elastohydrodynamic (EHD) lubrication, lubricant material (lubricant), rheological and tribotechnical properties, rolling friction.

Introduction

Although lubrication is necessary for the satisfactory operation of rolling bearings, the effect of lubricant on the fatigue life of the bearing has not been sufficiently studied. In recent times, the theory of elastohydrodynamic (EHD) lubrication [1] has been used to explain the different effects of lubricants. According to this theory, the thickness of the lubricating layer separating the moving elements of the bearing is determined by the viscosity-pressure dependence of the lubricant. The contact of surface micron irregularities does not occur if it is possible to maintain a sufficient thickness of the lubricating layer - in this case, the long-term durability of the bearing is ensured. If the film thickness is reduced to a level where surface irregularities are encountered, the fatigue life rapidly decreases with increasing contact frequency. In any case, a comprehensive calculation methodology is needed that would allow to take into account the influence of lubricant on the fatigue life of bearing units.

The purpose of the work

To develop a comprehensive methodology for assessing the influence of lubricant on rheological and tribotechnical properties under rolling friction conditions for bearing units.

Technique for researching the properties of coatings for the influence of lubricant material.

For modern multigrade transmission, aviation and motor-transmission oils, it is necessary to evaluate the dynamic viscosity on a rotational viscometer in order to approximate the real operating conditions of various bearing units - namely, at high shear rates to ensure mechanical stability and film strength under high contact pressure, maximum contact and sub-surface tangential stresses and deformations, which is the cause of fatigue wear of the ball and sections of the friction paths of the bearing cage.

Of great importance for the technology of lubrication of heavily loaded parts of tribomechanical systems are the conditions of formation of an elastohydrodynamic (EGD) lubricating layer in a local (point) friction contact, under which pressure significantly affects the viscosity of the lubricant, as well as the deformation of the contacting bodies (film shape). The viscosity of compressible fluids increases with increasing pressure. The relatively low compressibility of mineral and synthetic oils leads to a significant increase in viscosity at high pressures.

Consequently, at points subjected to high load, the effective viscosity becomes higher than the nominal viscosity of oils at equal temperatures. At the same time, an increase in temperature under such conditions leads to a decrease in the effect of viscosity increase with increasing pressure. Also very important is the influence of the rheological behavior of the oil, which is observed, for example, when the dynamic viscosity increases with respect to atmospheric pressure and temperature at the entrance to the contact, which leads to an increased effect on the change in viscosity with increasing pressure and temperature.

This special (non-Newtonian) rheological behavior of the oil with increasing pressure and temperature leads to a strong dilution of the structural viscosity of the oil due to the addition of polymeric viscosity modifiers to the base base to extend the viscosity-temperature range of operation, which, when the temperature changes, shrink/expand, bringing the characteristics of the base bases to the required values. At high shear rates, polymers line up in the direction of flow and shrink, resulting in oil thinning. In addition, some polymers at high shear rate, on the contrary, thicken (expand their volume), and the fluidity characteristics of such fluids somewhat lose linearity depending on temperature.

Taking care of this problem, it was necessary to develop a methodology for calculating rheological and tribotechnical characteristics, simulating real operating conditions for various bearing units.

As oils, were investigated: two multigrade gear oils with different viscosity classes SAE 75W-90 and SAE 80W-90 (manufactured by KSM PROTEC), respectively, which are used for most friction units of the transmission of passenger cars, trucks and agricultural machinery; aviation oil MS-8p (MS-8pn, manufactured by ZTM "ARIAN") for lubrication of friction bearing units of gas pumping units based on aviation GTD and universal motor-transmission oil MT-8p (EMT-8, manufactured by ZTM "ARIAN") for lubrication of friction units of auxiliary internal combustion engine (up to 35 hp) and transmissions of military vehicles. s.) and transmissions of military and agricultural tracked vehicles.

Dynamic viscosity (η) is a measure of the resistance to fluid flow or deformation. The dynamic viscosity of an oil (η) at temperature (t) is calculated from the kinematic viscosity using the following formula:

$$\eta = \upsilon\,\rho, \qquad (1)$$

where υ is the kinematic viscosity, mm^2/s.

ρ is the oil density at the same temperature at which the kinematic viscosity υ was determined, g/sm^3;

From the point of view of the rheological characteristics of the oils under study, a more universal definition of dynamic viscosity should be used, which would be equally suitable for Newtonian and non-Newtonian oils. For this purpose, the dynamic viscosity is defined as the ratio of shear stress (τ) and shear rate (D):

$$\eta_0 = \frac{\tau}{D}, \qquad (2)$$

Measurement of dynamic viscosity (η_0) at atmospheric pressure and temperature at the contact inlet is carried out by means of a rotational viscometer (Fig. 1) using a coaxial-cylindrical measuring device (Fig. 2).

When determining the dynamic viscosity, rotational viscometers have the advantage that they allow to measure viscosity as a function of time at high shear rate up to 10^6 s^{-1} and to determine the presence of hysteresis of elastic-viscous properties.

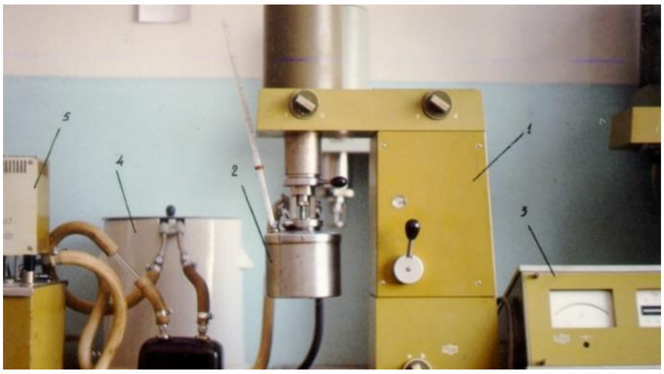


Fig. 1. General view of the rotational viscometer REOTEST 2.1.

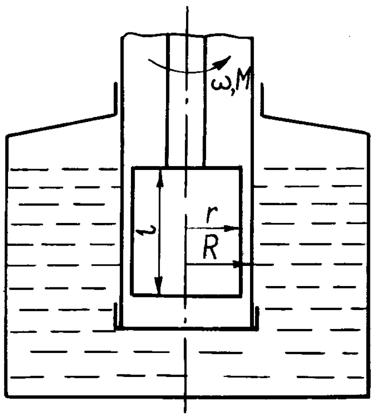


Fig. 2. Scheme of the coaxial-cylindrical system REOTEST 2.1.

Shear stress (τ) and shear rate (D) are determined according to the following relations:

- Shear stress (τ):

$$\tau = \frac{M}{2\cdot\pi\cdot l\cdot r^2}; \qquad (3)$$

- Shear rate (D):

$$D = \frac{2 \cdot \omega \cdot R^2}{R^2 - r^2}; \quad (4)$$

To determine the dynamic viscosity as a function of pressure, the exponential law [1] of the viscosity-pressure relationship described by the Barus dependence is used:

$$\eta = \eta_0 \cdot e^{\alpha \cdot P}, \quad (5)$$

where η is the viscosity at pressure P; η_0 is the viscosity at the contact inlet at P = 0; α is the coefficient of dependence of viscosity on pressure (piezo-viscosity coefficient).

The piezo-viscosity coefficient (α) [2] characterizes the effective viscosity with changing pressure and temperature and is determined by the following equation:

$$\alpha \cdot P = A \cdot \left[\left(\frac{T - 138}{T_0 - 138} \right)^{-S_0} \cdot B^Z - 1 \right], \quad (6)$$

where $A = ln(\eta_0) + 9{,}67$ – rheological constant for the oil under study;
$B = 1 + 5{,}1 \cdot 10^{-9} \cdot P_{max}$, *Pa;*
η_0 – dynamic viscosity at $P_{max} = 0$, *Pa·s*;
P_{max} – maximum Hertzian pressure, *Pa;*
T_0 – atmospheric temperature, *293 K (20^{0}C);*
$Z = 0{,}67$ – a constant that depends on the pressure P_{max};
S_0 - a constant that depends on temperature (T) and can be found by the following relation:

$$S_0 = \frac{\beta \cdot (T_0 - 138)}{A}, \quad (7)$$

where β – thermal viscosity coefficient.

In the conditions of EGD lubrication mode, the time of passage of the lubricant through the contact zone is very short, and the process is accompanied by large changes in pressure, temperature, stress and shear rate gradients. Under this friction regime, even lubricants of mineral origin, which are traditionally considered Newtonian, can show deviations from this model.

Non-Newtonian fluid is characterized by the fact that the shear stress between the layers is not directly proportional to the shear rate. It can also be characterized by a shear stress and depend, in addition to the velocity gradient in the oil flow, on temperature, pressure, etc.

The rheological behavior of oils depends to a large extent on the frequency of loading, because at short-term but high-frequency loads, corresponding, for example, to rolling bearings, the oil measured in the pressure zone does not have time to relax and acquire the input properties. Therefore, at excessive pressure and shear rate, the influence of viscoelasticity (rheology) on the thickness of the lubricating layer is noticeable. Non-Newtonian properties, which change the value of normal and tangential stresses, significantly affect the friction force and the thickness of the lubricating layer.

Thus, there are cases when some oils, which under normal conditions act according to the laws of Newtonian fluid, in some cases, in particular under high-speed, high-load and high-temperature conditions, can behave as non-Newtonian fluids, distorting the results obtained theoretically. At the same time, the minimum and central thickness of the lubricating layers between the friction surfaces of the bearing units change significantly.

The main characteristic of the point contact - the central thickness of the lubricating layer (H_0) - can be generalized as a function of the change of three dimensionless parameters of speed (U), load (W) and material properties (G), which can be written in the following form for the point (circular) friction contact [2]:

$$H_o = 3{,}49 \cdot U^{0{,}75} \cdot W^{-0{,}206} \cdot G^{0{,}426}. \quad (8)$$

The dimensionless parameters in the above formula are defined as follows:

1. Dimensionless film thickness in the central contact area:

$$H_0 = \frac{h_0}{R}. \quad (9)$$

2. Dimensionless velocity parameter:

$$U = \frac{\eta_o \cdot V}{E' \cdot R}. \quad (10)$$

3. Dimensionless load parameter:

$$W = \frac{F}{E' \cdot R^2}. \quad (11)$$

4. Dimensionless parameter of materials:

$$G = \alpha \cdot E'. \quad (12)$$

Results of calculations for the influence of lubricant materials

Table 1 shows the input data and formulas for calculations:

Table 1

The input data and formulas for calculations.

Modulus of elasticity of steel $E_1 = 2{,}07 \cdot 10^{11}$ *Pa*	The reduced radius of curvature $R = 6{,}35 \cdot 10^{-3}$ *m*
Modulus of elasticity of glass $E_2 = 0{,}757 \cdot 10^{11}$ *Pa*	Rolling velosity *V = 1,2 m/s*
Poisson's ratio of steel $\upsilon_1 = 0{,}3$	Temperature at the contact inlet *T = 293K*
Poisson's ratio of glass $\upsilon_2 = 0{,}25$	Operating temperature in contact *T = 343K*
Reduced modulus of elasticity $E' = \frac{2}{\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)} = 1{,}19186 \cdot 10^{11}, Pa$	Thermal viscosity coefficient, β: *β (MS-8p) = 0,027;* *β (SAE 75W-90) = 0,030;* *β (MT-8p) = 0,030;* *β (SAE 80W-90) = 0,045.*
Dynamic viscosity in atmospheric conditions at the entrance to the contact, η_0, *Pa·s:* η_0 *(MS-8p) = 0,185;* η_0 *(SAE 75W-90) = 0,244;* η_0 *(MT-8p) = 0,264;* η_0 *(SAE 80W-90) = 0,478.*	Dynamic viscosity η depending on pressure and temperature is calculated by formula (5). The piezo-viscosity coefficient α is calculated by formula (6).

Calculations of the change in dynamic viscosity η/η_0 with pressure and temperature (rheological properties) and the change in the central thickness h_0 of the lubricating layer with pressure and temperature (tribotechnical properties) were made for two multigrade gear oils with different viscosity classes SAE 75W-90 and SAE 80W-90, respectively, aviation oil MS-8p and universal motor-transmission oil MT-8p, and the corresponding results are presented graphically (Fig. 3 - 4).

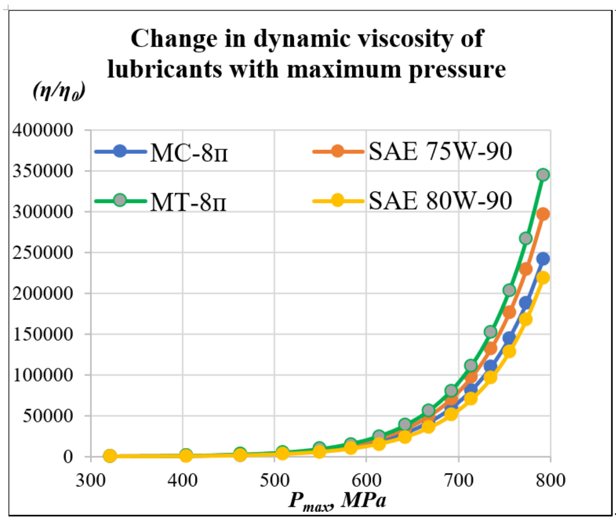


Fig. 3. Influence of the rheological feature (change in dynamic viscosity) of lubricants of different physical and chemical composition with increasing maximum pressure, taking into account the temperature in the contact zone T = 343 K for friction bearing units

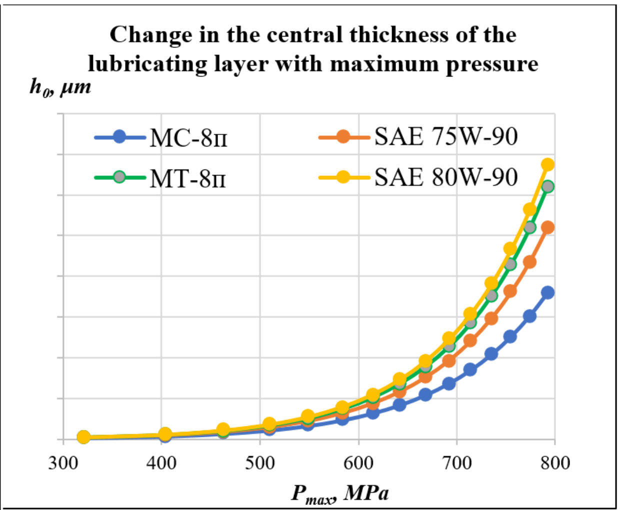


Fig. 4. Change in the central thickness of the lubricating layer with increasing maximum pressure, taking into account the temperature in the contact zone T = 343 K for friction bearing units lubricated with lubricants of different physical and chemical composition

Conclusions

A complex method of calculation of the influence of rheological and tribotechnical properties of the lubricant with increasing maximum pressure, taking into account the temperature in the point contact zone, which indirectly expresses the fatigue life of bearing units under EGD lubrication conditions, is presented.

References

1 Dmitrichenko N.F. The Elastohydrodynamics: Theory and Practice / N.F. Dmitrichenko. - Lviv: Publishing house of National University "Lviv Polytechnic", 2000. – 224p.

2. Dmytrychenko M.F. Lubricating action of oils in conditions of elastohydrodynamic lubrication / M.F.Dmytrychenko, O.A.Milanenko - K.: Informavtodor, 2009. 184p.

Міланенко О., Савчук А., Туриця Ю. Вплив мастильного матеріалу в зоні точкового контакту на втомну довговічність в умовах тертя кочення для підшипникових вузлів тертя.

Представлена комплексна методика розрахунку впливу реологічних й триботехнічних властивостей мастильного матеріалу при збільшенні максимального тиску з урахуванням температури в зоні точкового контакту, що опосередковано виражає втомну довговічність підшипникових вузлів в умовах ЕГД мащення. Встановлено, що для найбільш високов'язкої трансмісійної оливи SAE 80W-90 характерна найменша залежність динамічної в'язкості від максимального тиску, з урахування того, що дана трансмісійна олива створює більші товщини мастильного шару, що підтверджує наші припущення про те, що для високонавантажених трансмісій потрібно використовувати трансмісійні оливи більшої в'язкості.

Нехарактерні кращі реологічні властивості (найменша залежність динамічної в'язкості від максимального тиску при певній температурі в зоні контакту) найбільш високов'язкої трансмісійної оливи SAE 80W-90 підтверджують уявлення про те, що, крім обмеженого впливу в'язкості оливи, втомну довговічність визначають і й хімічний склад оливи, що обумовлює селективні хімічні реакції між окремими компонентами (поверхнево-активними речовинами) оливи та металічними поверхнями.

Ключові слова: Точковий контакт тертя, втомна довговічність, підшипники кочення, еластогідродинамічне (ЕГД) мащення, мастильний матеріал, реологічні і триботехнічні властивості, тертя кочення.

Problems of Tribology, V. 28, No 2/108-2023, 20-27

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-20-27

Nitriding in a cyclically switched glow discharge

M.S. Stechyshyn[1], O.V. Dykha[1*], V.P. Oleksandrenko[1], N.M. Stechyshyna[2]

[1]*Khmelnitskyi National University, Ukraine*
[2]*WU (Vienna University of Economics and Business), Austria*
**E-mail:tribosenator@gmail.com*

Received: 15 April 2023: Revised: 25 April 2023: Accept:23 May 2023

Abstract

The paper shows the prospects of nitriding in a cyclically switched discharge, the classification of nitriding processes in a glow discharge according to the criteria of the characteristics of the power source is given. A comparison of the advantages and disadvantages of nitriding processes with constant and cyclically switched discharge is given.From a theoretical point of view, the process of nitriding in a cyclically switched glow discharge is considered based on the concept of an energy model. In accordance with this model, tasks for further theoretical and experimental research are formulated. It is shown that the process of surface modification in a cyclically switched discharge opens up new possibilities associated with variants of the CSD itself, which is characterized by: frequency, period and pulse shape. The implementation of the process of adjusting the switching frequency, pitch - the ratio of the cycle period to the duration of the signal, and the shape of the signal itself opens up wide opportunities to significantly influence the results of surface treatment.

The influence of the shape of the discharge power signal on the kinetics of the nitriding process and its results opens up wide opportunities for studying the process itself. The presence of surges at the beginning and at the end of the cycles can, in principle, significantly affect both the nature of the nitriding process itself and the structure and phase composition of the modified surface layer, since short-term and sufficiently powerful voltage surges should lead to intensive surface sputtering. The destruction of the monolayer of nitrides, which has just formed on the surface, will contribute to the increase of the depth of the nitrided layer due to the diffusion of nitrogen particles, as well as to a certain extent leveling off the blocking effect of the surface nitride layers.

Keywords: nitriding, glow discharge, cyclic switching, discharge power, waveform, nitride layer depth

Introduction

Nitriding in a glow discharge with constant or conditionally constant power is traditionally used as one of the effective methods of surface modification of metals. For this method of strengthening metal surfaces and alloys, both the main theoretical provisions and practical recommendations for its application have been established [1-3].

Nitriding in a cyclically switched (intermittent) glow discharge (CSD) opens up fundamentally new possibilities both theoretically and technologically. First of all, this concerns a significant simplification of the principles of the formation of the cage, as well as the danger of the glow discharge turning into an arc. Despite the obvious new possibilities opened up by the application of processes in a cyclically switched glow discharge, theoretically this process has hardly been developed, which, of course, does not contribute to the use of all its potential. A separate aspect in the theory of the nitriding process in a cyclically switched discharge is its interpretation from the energy point of view, since in the end all elementary sub-processes are fundamentally regulated by energy prerequisites. By creating certain energy parameters of the process, it is possible to stimulate or, on the contrary, inhibition of the main competing components: formation of nitrides, diffusion of nitrogen into the depth of the surface, sputtering of surface layers. The characteristics of tribological systems on the modified surface of metals depend on the ratio of these components. In addition, the question of the adequacy of the evaluation of the results of surface modification to the practical performance indicators of the modified products is essential. The process is absolutely environmentally friendly. The principle of modification of the metal surface, which is used in the researched process, provides the most favorable economic prerequisites compared to other technologies similar in purpose, primarily due to extremely low energy costs. the ratio of these components depends on the characteristics of tribological systems on the modified surface of metals. In addition, the question of the adequacy of the evaluation of the results of surface modification to the practical performance indicators of the modified products is essential. The process is absolutely environmentally friendly. The principle of modification of the metal surface, which is used in the researched process, provides the most favorable economic prerequisites compared to other technologies similar in purpose, primarily due to extremely low energy costs. the ratio of these components depends on the characteristics of tribological systems on the modified surface of metals. In addition, the question of the adequacy of the evaluation of the results of surface modification to the practical performance indicators of the modified products is essential. The process is absolutely environmentally friendly. The principle of modification of the metal surface, which is used in the researched process, provides the most favorable economic prerequisites compared to other technologies similar in purpose, primarily due to extremely low energy costs.

Classification of nitriding processes

The general systematization of surface modification processes using glow discharge qualifies them as vacuum-diffusion gas discharge [2, 4, 5]. Most of the theoretical studies of the process refer to one of its possible variants, where the power source is continuously loaded on the discharge chamber. However, in principle, other power options are also possible, and in this case, certain technological advantages are achieved.

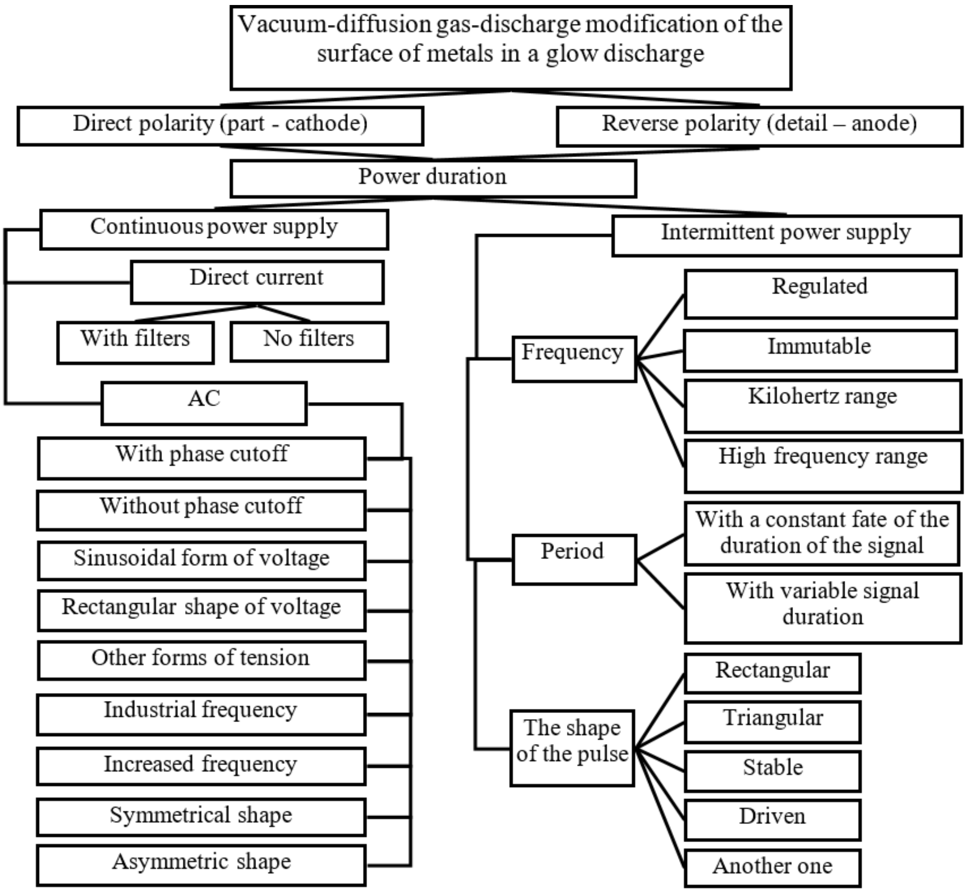


Fig. 1. Classification of nitriding processes in glow discharge according to the criterion of power source characteristics

Consideration of nitriding in a glow discharge precisely according to the criterion of continuity of power leads to the scheme shown in Fig. 1. In the vast majority of cases, nitriding installations in glow discharge were formed according to the scheme of direct polarity (conventional name), in which the part is the cathode. In theory, the doctrine prevailed, according to which nitriding of parts to which the positive pole of the power source is attached (reverse polarity) is impossible [6]. However, later a number of studies were conducted, including experimental ones, which proved that nitriding is possible even with such a feeding scheme. At the same time, it is only important to provide a method other than cathodic bombardment to heat the parts to the temperature regulated by the technological regime. This version of the process is especially effective when using an arc discharge, when the current density is significantly higher compared to glow discharge [7]. In the future, the nitriding method with reverse polarity, in the case of sufficient theoretical work, can be used as one of the really possible options, since it creates conditions for a relatively low energy of the incident flow in the area of nitride formation energies. Thus, the low-energy spectrum of the incident flow may contribute to the growth of the activity of nitride formation while reducing the intensity of their sputtering [8].

In chronological order, technologies with continuous power supply were introduced first. Such systems are fundamentally simpler, and, most importantly, ensure the transfer of a greater amount of energy to the falling flow and, accordingly, to the processed parts. In the complex, this contributes to a greater intensity of modification and a shorter duration. Better stability of the discharge is observed when using ripple filters, but this complicates power supply units and their cost, in addition, electricity costs increase [2].

In AC power supply units, there are options for completely or partially cutting off one of the phases (as a rule, the positive one, if a process with direct polarity is used). Without such a cut-off, the heating of the anode, as a rule, the walls of the chamber increases and the intensity of nitriding decreases. However, the latter can lead to a softer regime of nitriding, in accordance with better indicators of plasticity of the modified layer. A certain reduction of the negative influence of the positive phase on the nitriding process can be achieved by the asymmetry of the voltage shape due to the displacement of its average value in the negative zone. In principle, the shape of the voltage can be sinusoidal, rectangular or arbitrary up to its programmed change. It is obvious that the use of a rectangular voltage form with other constant parameters provides a greater energy saturation of the incident flow, accordingly, the regime is more rigid, but the processing time is shorter. The simplest is the option of using the transformed voltage of the industrial frequency, because it eliminates the need to use rectifiers. High-frequency current feeding is somewhat similar in principle (excluding the effect of the positive phase) to nitriding with intermittent feeding.

Nitriding with constant feeding has a significant technological disadvantage. It consists in the increased complexity of garden formation. This is primarily due to the fact that in all places where there are gaps larger than 0.5 mm, local burning of the discharge occurs, but already in the arc mode. This leads to local overheating of the parts, and in some cases, to the impossibility of conducting the process, because an arc occurs when trying to increase the voltage in such places. The need to take into account the mentioned circumstance complicates the construction of hangers or tables that would ensure a tight base of parts on them. However, even when the condition of a tight base of the part on the table is met, the presence of chamfers on the supporting surface of the parts also causes a certain problem, since it together with the supporting surface of the table forms a wedge-shaped gap. Another drawback, especially in comparison with gas furnace nitriding, there is a low efficiency of modification of holes, especially of small diameter, with their relatively long length. From the theory of discharge with a hollow cathode, it is known that the field strength in the hole is practically zero at a depth of more than two diameters [2]. The necessary results of nitriding of the holes can be achieved due to a significant increase in the duration of the treatment, but in such a setting, all other advantages of nitriding in the glow discharge are negated, especially in terms of duration, since in this case the process follows the scheme of ordinary furnace gas nitriding.

Nitrogenation in the CSD

In recent years, nitriding technologies in glow discharge with intermittent power supply - cyclically switched discharge (CSD) - have been used in increasingly noticeable volumes. The main principle of the formation of the CSD is that the duration of the signal in the cycle should not be longer than the time of the transition of the glow discharge to the arc, and the pause should not be less than the extinguishing of the arc discharge, if it even occurred. Under such conditions, there is practically no need for automatic arc discharge cutting devices, or they can be used according to a scheme with an extremely simplified algorithm. The cage can be formed in compliance with the requirements, which are no more complicated than in the case of ordinary furnace nitriding. In other words, if we ignore the issue of uneven surface temperature distribution caused by mutual heating from the adjacent part, then in the garden they can be placed practically in a heap or use any supporting surfaces, hooks for hanging, etc. At the same time, existing local surface exceptions, gaps, etc., play almost no negative role. It has been experimentally established that, using CSD, it is possible to nitride small-diameter holes with a relatively significant depth [9, 10]. However, since the energy transfer to the falling flow takes place only in part of the cycle, the efficiency of nitriding is lower, and in some cases the actual nitriding phase is two or even more times longer than with continuous nitriding [11]. By the way, with regard to the terminology used in this work, it should be noted that it is fundamentally incorrect, since we deal with voltage pulsations all the time even during normal nitriding, especially in cases where filters are not used.

Intermittent power supply with the help of CSD is characterized in terms of classification by several characteristics: frequency or period and pulse shape. It would be optimal to be able to adjust the switching frequency, since it, together with the ability to change the frequency - the ratio of the cycle period to the duration of the signal - will have the most significant effect on the processing results. The option using a high-frequency field allows the use of standard power generators (provided that the positive phase is cut off), although there are problems with the shielding of the installation elements to prevent the occurrence of radio interference. If sources are used that allow adjusting the gap, then in principle it is possible to implement both continuous and intermittent power supply options in one installation. Such versatility allows you to optimally use the potential possibilities of the process, because in the presence of complications related to the shape of the parts (local exceptions, holes, etc.), you can use CSD, while the period of the actual nitriding phase will increase. If the shape of the part is not complicated. then it is advisable to switch to a more productive continuous power supply method. A similar choice can be made when there is a need to apply less rigid technological regimes. With regard to the shape of the pulse, this question should first of all be considered as an object of theoretical studies of the formation of the energy spectrum of the falling flow under alternating voltage, both in the phase of voltage increase and its decrease. A certain role, perhaps in this sense, can be played by tension fronts. parts related to the shape (local exceptions, holes, etc.) can be used by CSD, while the period of the actual nitriding phase will increase. If the shape of the part is not complicated. then it is advisable to switch to a more productive continuous power supply method. A similar choice can be made when there is a need to apply less rigid technological regimes. With regard to the shape of the pulse, this question should first of all be considered as an object of theoretical studies of the formation of the energy spectrum of the falling flow under alternating voltage, both in the phase of voltage increase and its decrease. A certain role, perhaps in this sense, can be played by tension fronts. parts related to the shape (local exceptions, holes, etc.) can be used by CSD, while the period of the actual nitriding phase will increase. If the shape of the part is not complicated. then it is advisable to switch to a more productive continuous power supply method. A similar choice can be made when there is a need to apply less rigid technological regimes. With regard to the shape of the pulse, this question should first of all be considered as an object of theoretical studies of the formation of the energy spectrum of the falling flow under alternating voltage, both in the phase of voltage increase and its decrease. A certain role, perhaps in this sense, can be played by tension fronts. A similar choice can be made when there is a need to apply less rigid technological regimes. With regard to the shape of the pulse, this question should first of all be considered as an object of theoretical studies of the formation of the energy spectrum of the falling flow under alternating voltage, both in the phase of voltage increase and its decrease. A certain role, perhaps in this sense, can be played by tension fronts. A similar choice can be made when there is a need to apply less rigid technological regimes. With regard to the shape of the pulse, this question should first of all be considered as an object of theoretical studies of the formation of the energy spectrum of the falling flow under alternating voltage, both in the phase of voltage increase and its decrease. A certain role, perhaps in this sense, can be played by tension fronts.

Theoretically, the process of nitriding in a cyclically switched glow discharge (CSGD) is supposed to be considered based on the concept of the energy model [2, 12]. The main differences and additions to previously performed theoretical studies are reduced to the following:

1) the kinetics of the movement of the particles of the incident current in the near-cathode zone will have a feature related to the fact that at the moment of pause (absence of voltage) the charged particles will no longer move under the influence of the electric field strength, but by inertia tangential to their previous one at the moment of removal potential of the trajectory field;

2) a change in the kinetic dependences, including the values of the parameters of the motion of the mediated particle, will affect the probabilistic characteristics of the falling particles reaching the cathode, as well as the angular parameters of their collision with the surface. In turn, the angular characteristics will change the conditions of energy transfer from the particles of the incident flow to the surface components;

3) removing the field tension at certain moments of particle movement will stop their accumulation of kinetic energy, which will affect the distribution of particles by energy levels;

4) therefore, the energy spectra of the incident flow will change, depending not only on the traditional parameters of the technological regime, but also on the characteristics of the specified CSD;

5) since all the main indicators of the energy model - relative energy factors primarily depend on the shape of the energy spectra, the change of the latter requires additional research;

6) the formation of the structure of the modified layer also changes, the main dependences of the processes of phase formation during CSD require separate studies;

7) the most significant consequence of the processes of formation of tribotechnical systems is the study of the influence of their structure on the wear resistance of modified layers. The practical result is the establishment of regularities of technological process control depending on the necessary processing results, formed on the basis of the requirements of the conditions of the subsequent operation of the objects;

8) for the practical application of the positive nitriding factor of small-diameter holes when using CSD, it is necessary to develop a theory of changes in the concentration of diffusants in relatively long holes;

9) since the energy balance of plants operating with the use of CSD can significantly differ from the similar indicator of plants with continuous power, this issue requires a separate study;

10) when applying CSD, conditions are created for controlling the intensity of phase formation by changing the rigidity of the technological regime, therefore, the issue of nitriding in CSD of nitrogen-active metals is of particular practical interest;

11) it is also necessary to investigate the possible influence on the NCSD process of the shape of the voltage change and the deviation of this shape from the ideal;

12) an important role will be played by the processes in the internal local exceptions of the surface, since it will be necessary to compare the behavior of such surface elements in the process of nitriding under different power options;

The noted problems form the basis of a new scientific and technical task - nitriding of metals in a cyclically switched discharge. The practical implementation of the research results is primarily aimed at using the positive properties of nitriding processes with intermittent discharge discharge.

Hardware implementation of nitriding in CSD

According to the data given in works [9-10], the introduction of the cyclic switching mode during nitriding in the glow discharge opens up additional opportunities to improve the efficiency and quality of the specified technology, primarily:

- the possibility of nitriding parts of a complex shape is expanded (the presence of deep and narrow grooves, small-diameter holes, long holes, etc.);
- the risk of local damage to modified surfaces is reduced by reducing the probability of arc discharges;
- the permissible range of adjustment of parameters important for optimizing the technological process, such as the pressure in the discharge chamber and the temperature of the surface of the parts, is expanded;
- the control of preventing overheating of the surface is significantly simplified due to the release of additional discharge energy.

The development of the experimental layout of the device for the implementation of cyclic switching of the gas discharge was based on the following prerequisites:

- maximum compatibility with existing electrical and electronic equipment;
- use of available element base;
- the possibility to provide a sufficiently wide range of switching parameters for the purpose of further optimization of modes and their comparative analysis;
- reliable equipment protection against overloads and abnormal situations.

The justification of the switching parameters is primarily based on the following requirements for the pulse current source:

- the shape of the pulse should be rectangular, which would ensure a jump from the zero level to the desired zone of anomalous glow discharge;
- the duration of the pulse should be shorter than the arc development time (approximately less than 100 μs), while the formation of the arc is disturbed; if necessary, the current can be interrupted during any pulse;
- the pause that follows each pulse should be short enough to ensure easy ignition of the discharge under the action of the next pulse, i.e. be less than a few milliseconds;
- the ratio of the duration of the pulse and the pause should vary widely to effectively control the heating of the parts.

Typical values of the pulse duration, which are recommended in [10], are in the range from 20 to 100 μs, while the pause duration can vary from 20 to 200 μs. It should be noted that the processes of ignition and extinguishing of the discharge are characterized by significant inertia, and this circumstance imposes certain restrictions on the choice of time parameters of switching. Moreover, the inertia of gas discharge processes may depend on the geometry of the discharge space and its dimensions, which in real conditions can vary in a very wide range. The conclusion follows that it would be imprudent to unconditionally transfer the recommendations [10, 13], which were developed on an experimental installation with a chamber with a diameter of 400 mm and a height of 600 mm, to the case of much larger installations. The same applies to the results, obtained in the process of physical research of miniature gas discharge devices (the so-called laboratory discharge). However, it was decided at this stage of development to provide a sufficiently wide range of current switching parameters in order to refine it after conducting a series of preliminary experiments. Namely, we specify the ranges of variation of the frequency f of pulse tracking from one to ten kilohertz, the filling factor of the period from zero to one:

$$\eta = t_n / T = 0...1,$$

where T is the pulse tracking period $T = 1/f$,

t_n is the duration of the pulse (duration of the active part of the period).

In order to save time and costs, it was decided to use the power supply unit of the existing plants for nitriding in the glow discharge and the corresponding control devices (CSD - nitriding process controller), as well as current and discharge voltage sensors. To implement the pulse mode of the installation, the power supply unit is additionally equipped with a T-shaped RC - smoothing filter and a specially developed intermittent mode controller (IMC), which includes a power electronic key EC with a control and protection device.

For the construction of the power switch, a powerful transistor of the MOSFET structure was chosen, which is characterized by the following advantages, first of all - in comparison with bipolar transistors:

- low power of consumption in management circles;
- good characteristics when working in parallel, which makes it relatively easy to increase the power of the key (up to certain limits).

At the same time, as with the use of bipolar transistors, in this case there is an urgent problem of protection against current overloads, which sharply reduce the reliability of the key.

The device for implementing cyclic switching of a gas discharge is described in detail in [14].

The practical implementation of the device on a nitriding installation in a smoldering cyclic-commutated discharge confirmed its operability in the conditions of real technological processes. At the same time, all the planned prerequisites mentioned above have been achieved, which opens the way to the experimental use of cyclically switched discharge for surface modification of metal alloys on a fundamentally new basis. The application of this method allows solving a number of technological problems, the most important of which is the modification of parts of a complex shape, with holes and depressions of small transverse and large dimensions. It was possible to effectively nitride such parts only with the use of furnace nitriding in ammonia gas environments, that is, a process that is unacceptable in modern conditions not only in view of its economic indicators, but also, first of all, from the point of view of environmental safety. In addition, the probability of surface damage caused by the accidental transition of a glow discharge to an arc, which is often observed when using continuous power supply of the discharge chamber, is significantly reduced.

Practical implementation of nitriding in CSD

The presence in the installation scheme of the block of cyclic switching of the discharge does not exclude the possibility of using the equipment in the constant discharge mode, providing for the possibility of mobile variation of the modes: constant and switched.

In AC power supply units, it is possible to completely or partially cut off one of the power lines (as a rule, the positive one, if a process with direct polarity is used). The absence of such a cut-off helps to increase the heating of the anode, which leads to a decrease in the intensity of the process. However, such a phenomenon can lead to softening of the nitriding process itself, obtaining better indicators of plasticity of the modified layer. A certain reduction of the negative influence of the positive phase on the nitriding process can be achieved by the asymmetry of the voltage shape due to the displacement of its average value in the negative zone. In principle, the shape of the voltage can be sinusoidal, rectangular or arbitrary up to its programmed change. The influence of the signal shape on the process of formation of the modified surface layer requires a separate study. Obviously, that the use of a rectangular form of voltage with other constant parameters ensures a greater energy saturation of the incident flow, correspondingly, a greater rigidity of the regime, with a shorter duration of processing. The simplest is the option of using a transformed industrial frequency voltage, which is somewhat similar in principle (excluding the effect of the positive phase) to nitriding with intermittent power supply.

The use of cyclically switched power discharge of the discharge chamber, which is carried out by current in the form of an intermittent signal, has a number of significant advantages:

- the possibility of forming such a CCR, in which the duration of the signal in the cycle does not exceed the time of transition of the glow discharge into the arc. The duration of the pause is not less than the extinguishing time of the arc discharge, in the event of its occurrence, which negates the need for automatic arc discharge cut-off devices, or they can be used according to a scheme with an extremely simplified algorithm;

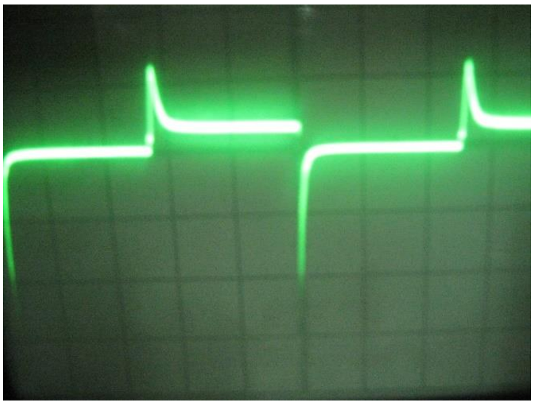


Fig. 2. The shape of the change in the discharge current with a cyclically switched discharge of a rectangular shape with a slit $\gamma = 2$.

- the process of forming the cage is significantly simplified, since the need to comply with the requirements for gaps and deep holes practically disappears;
- there is an opportunity to nitride holes of small diameter with a relatively significant depth;

It should be noted as a disadvantage when using the CSD that the energy transfer to the falling flow takes place only in that part of the cycle where the signal is active and the efficiency of the process is lower, and in some cases the nitriding phase is two or even more times longer than with a continuous discharge. The nature of the change in current during a cyclically switched discharge is shown in Fig. 2, voltages - in fig. 3.

However, in general, the surface modification process in a cyclically switched discharge opens up new possibilities associated with variants of the CCR itself, which is characterized by: frequency, period and pulse shape. The implementation of the process of adjusting the switching frequency, pitch - the ratio of the cycle period to the duration of the signal, and the shape of the signal itself opens up wide opportunities to significantly influence the results of surface treatment.

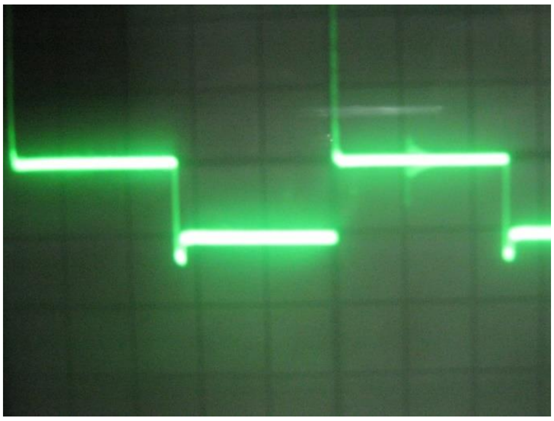


Fig. 3. The shape of the discharge voltage change with a CSD of a rectangular shape with a slit $\gamma = 2$.

The influence of the shape of the discharge power signal on the kinetics of the nitriding process and its results opens up wide opportunities for studying the process itself. The presence of surges at the beginning and at the end of the cycles can, in principle, significantly affect both the nature of the nitriding process itself and the structure and phase composition of the modified surface layer, since short-term and sufficiently powerful voltage surges should lead to intensive surface sputtering. The destruction of the monolayer of nitrides, which has just formed on the surface, will contribute to the increase of the depth of the nitrided layer due to the diffusion of nitrogen particles, as well as to a certain extent leveling off the blocking effect of the surface nitride layers.

Conclusions

The use of cyclically switched discharge nitriding in glow discharge technology allows to obtain adjustable and even predictable processes of surface modification of metals and alloys, formation of surface layers with specified properties, especially for parts of complex configuration.

References

1. Stechyshina N.M. Corrosion-mechanical wear resistance of food production equipment parts: monograph / N.M. Stechyshina, M.S. Stechyshyn, N.S. Mashovets – Khmnelnytskyi: KhNU, 2022.-181p.

2. Shepherd I.M. Theory and practice of hydrogen-free nitriding in a glow discharge. Kharkov: National Scientific Center "Kharkov Physical and Technical Institute", 2006. - 364p.

3. Caplun V.G. Ionic nitriding in hydrogen-free environments: monograph / V.G. Kaplun, P.V. Capon. – Khmelnytskyi: KhNU, 2015.–315p.

4. Pastor I. M.,Vacuum-diffusion treatment of the surface of metals with the use of glow and arc discharges in gases / I. M. Pastukh, A. A. Andreev, V. M. Shulaev // New thermal processes. Library OTTOM. - Kharkiv, NNC Khfty. – 2004. – P. 5 - 57.

5. Shepherd I. M.Modification of metals with the application of nitriding in the glow discharge: state and prospects / I. M. Pastukh // Problems of tribology. - Khmelnytskyi, 2004. - No. 3 - 4. -S. 42 - 55.

6. Vacuum - arc devices and coatings / A. A. Andreev, L. P. Sablev, V. M. Shulaev, S. N. Grigoriev. - Kharkov: National Scientific Center "Kharkov Physical and Technical Institute", 2005. - 238 p.

7. Shepherd I. M.Energy analysis of nitriding models in a glow discharge / I. M. Pastukh // Bulletin of the Khmelnytskyi National University. - Khmelnytskyi, 2006. - No. 5. - P. 7 - 14.

8. Kwon SC,. A comparative study between pulsed and DC ion nitriding behavior in specimens with blind holes / SC Kwon,. GH Lee, M. C Yoo // 1st International conference of ion nitriding. - Cleveland, Ohio. - 1986. - P. 77 - 81.

9. Grun R. Industrial advances for plasma nitriding / R. Grun // 2nd International conference on ion nitriding. – Cincinnati, Ohio. - 1989. - P. 157 - 163.

10. Bosyakov M.N., Equipment for hardening processing of machine and tool parts by the method of ion nitriding in the plasma of a pulsating current / M.N.Bosyakov, D.V. Zhuk, P.A. Matusevych // Col. acc. International conf. "Equipment and technologies of heat treatment of metals and alloys in mechanical engineering (OTTOM - 4)". - Part 2. - Kharkov: National Scientific Center "Kharkov Physics and Technology Institute". - 2003. - P. 271 - 276.

11. Pastukh I. M. Fiziko - technical treatment of the surface of metals by anhydrous nitriding in a glow discharge: Diss. dr. technical Sciences: 05.03.07./ I. M. Pastukh – Khmelnytskyi, 2008. – 520 p.

12. Dressler S. Plasma parameter control for industrial situations / S. Dressler // 2nd International conference on ion nitriding. – Cincinnati, Ohio. - 1989. - P. 183 - 193.

13. V.S. Kurskoi, V.V. Lyukhovets, O.S. Zdybel Hardware implementation of power supply of cyclically switched discharge in nitriding installations. // Bulletin of the Khmelnytskyi National University. Technical sciences. – 2017. – No. 3. – P. 27–31.

Стечишин М.С., Диха О.В., Олександренко В.П., Стечишина Н.М. Азотування в циклічно-комутованому тліючому розряді

В роботі показані перспективи азотування в циклічно-комутованому розряді, наведена класифікація процесів азотування в тліючому розряді за критерієм характеристик джерела живлення. Приводиться порівняння переваг і недоліків процесів азотування з постійним і циклічно-комутованим розрядом. В теоретичному плані процес азотування в циклічно-комутованому тліючому розряді розглядається виходячи з концепції енергетичної моделі. У відповідності до цієї моделі сформульовані завдання для проведення подальших теоретичних та експериментальних досліджень. Показано, що процес модифікації поверхні в циклічно комутованому розряді відкриває нові можливості, пов’язані з варіантами самого ЦКР, який характеризується: частотою, періодом та формою імпульсу. Реалізація процесу регулювання частоти комутації, шпаруватості – відношення періоду циклу до тривалості сигналу, та форми самого сигналу відкриває широкі можливості суттєво впливати на результати обробки поверхні.

Вплив форми сигналу живлення розряду на кінетику процесу азотування та його результати відкриває широкі можливості для дослідження самого процесу. Наявність сплесків на початку та в кінці циклів в принципі може суттєво впливати як на характер самого процесу азотування, так і на структуру та фазовий склад модифікованого поверхневого шару, оскільки короткочасні та достатньо потужні сплески напруги повинні призводити до інтенсивного розпорошення поверхні. Руйнування моношару нітридів, які щойно утворились на поверхні, сприятиме збільшенню глибини азотованого шару за рахунок дифузії часток азоту, а також нівелюватиме до певної міри блокуючий ефект поверхневих нітридних шарів.

Ключьові слова: азотування, тліючий розряд, циклічна комутація, живлення розряду, форма сигналу, глибина нітридного шару

Problems of Tribology, V. 28, No 2/108-2023, 28-36

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-28-36

Resistant Properties of Lubricating Materials with Fullerene Nanoadditives

V.P. Oleksandrenko[1*], V.V. Yefymenko[2], N.G. Kalmykova[2], O.V. Efimenko[2], R.V. Budiak[3], Yu. M. Nelyubin[1]

[1]*Khmelnitskyi National University, Ukraine*
[2]*National Aviation University, Ukraine*
[3]*Kalynivka Technological Applied College, Ukraine*
**E-mail:oleksandrenkovp@gmail.com*

Received: 22 April 2023: Revised:14 Mayl 2023: Accept:30 May 2023

Abstract

The purpose of this article is to study the possibility of using fullerene additives and their effect on the antiwear properties of aviation mineral and synthetic oils. The method of increasing the anti-wear properties of mineral MK-8p and synthetic Mobil Jet Oil 254 oil for turbojet aircraft engines by adding fullerene additive C60 is considered. It has been shown that the anti-wear properties of synthetic Mobil Jet Oil 254 oil for turbojet aircraft engines exceed MK-8p mineral oil by more than 10%. Increasing the concentration of fullerene additive in oils increases the wear resistance of conjugated surfaces. It was established that the increase in the concentration of the fullerene additive in oils shifts the critical load to higher values for both mineral and synthetic oils. The intensity of this growth is observed in mineral oil to a greater extent than in synthetic oil. The use of fullerenes as an anti-wear additive to oils for turbojet engines is proposed, which improves anti-friction properties and reduces the wear of parts of machines and mechanisms. Scientific progress is determined mainly by experimental research, the conduct of which in this direction is quite relevant.

Key words: fullerene additives, mineral oil, synthetic oil, four-ball machine, wear rate, critical load.

Introduction

The main function of lubricating oils and greases is to reduce friction and wear of the surfaces of parts that rub. An important place in increasing the reliability of the equipment and increasing its service life is occupied by the wear resistance of the parts. During operation, intensive wear of friction nodes occurs as a result of significant loads, speeds and temperatures, exposure to aggressive environments and vibrations. One of the most economically beneficial ways to increase the durability of friction nodes in various machines and mechanisms is to improve the quality of lubricants, primarily their lubricating properties, which is achieved mainly by introducing anti-wear, anti-seize and anti-friction additives into them. The introduction of additives into oils and lubricants allows you to satisfy two main requirements of technology: increasing the service life (reliability) of machines and mechanisms; fuel energy conservation, because about 30 % of the energy produced in the industrialized countries of the world is ultimately wasted on friction. In recent years, one of the ways to improve the operational properties of materials is the use of nanomaterials - fullerene as additives to them, including as additives to lubricating materials. This is due to the fact that these compounds are unique objects from the point of view of electronic structure, physical and chemical properties. An extraordinary feature is also the fact that it is the only soluble form of carbon in hydrocarbon compounds, which allows it to be used in a variety of directions. Conducting experimental studies on the possibility of using fullerenes and fullerene-containing carbon black as anti-wear additives is a very relevant area of scientific work.

Analysis of the latest research

Information on the study of the tribological properties of fullerenes is very scarce and mainly concerns fullerene C60. Several works have been published where fullerene C60 was studied in the form of a solid film as a solid lubricating coating, therefore it was concluded that C60 is promising for solving various tribological problems [1]. As shown in works [2-5], quite significant progress has recently been made in obtaining and researching nano-objects, new nanomaterials and nanotechnologies have emerged. Nanoclusters of a number of metals, fullerenes and carbon nanotubes were synthesized. A step forward was made in the methods of observing and studying the properties of carbon nanostructures, connected with the development of physicochemical methods of studying their use in lubricating materials. Research has been conducted, based on which it is proposed to use fullerenes as an antioxidant additive, which significantly improves the thermo-oxidative stability of oils in comparison with traditional additives.

Fullerenes are characterized by high chemical inertness in relation to the process of monomolecular decay. Thus, the C60 molecule retains its thermal stability up to a temperature of over 1500 °C, which cannot be said about other antiwear and antioxidant additives. However, in the presence of oxygen, the oxidation of this form of carbon to CO and CO_2 is observed already at significantly lower temperatures (about 250 ° C), but such a temperature is not reached in the lubrication system of modern automobile and aircraft engines, although in aviation supersonic aircraft when the engine is stopped, due to cessation of heat removal from the area of the turbine bearings, such an increase in temperature for a short period of time is possible [3].

The scientists performed a detailed quantitative study to determine the impact of fullerene additives on the performance characteristics of graphite-based lubricating compositions. The results of these studies can be used as a basis for the development of a "superlubricant" that will provide a coefficient of surface friction below 0.001.

As a lubricating base, highly oriented pyrolytic graphite (HOPG) was used, which, together with finely dispersed graphite powder of natural origin, was introduced into a mixture of concentrated sulfuric and nitric acids (in a volume ratio of 4:1) and stirred for 16 hours. The powder processed in this way was washed with water, dried at a temperature of 100°C, after which the sample was subjected to heat treatment for 15 seconds. This led to the formation of layered graphite particles, which were then introduced into a 70 % alcohol solution and subjected to ultrasonic treatment. Then, layered graphite particles together with C60 or C70 fullerene powder were sealed under vacuum in a quartz ampoule, which was kept at a temperature of 600 °C for 15 days. The graphite intercalated with fullerenes obtained as a result of the described procedure was used to obtain an anti-friction coating, which was a film with an area of 2.3x2.3 m2 and a thickness of 0.2 mm.

Fullerene-containing carbon black and powdered fullerene C60 provide a noticeable improvement in the antifriction and antiwear properties of steel-steel and copper-steel friction pairs, especially in the area of high loads and contact pressures. The greatest improvement occurs in the steel-steel friction pair. For copper pairs, it was determined that the presence of fullerene C60 in pure form or in fullerene carbon black leads to the formation of a fullerene polymer film of considerable thickness on the friction surface, which plays a protective role [6-8].

The coefficient of friction of this film μ was measured by the standard method as the ratio of the friction force to the applied lateral load. As a result of the measurement, values of $\mu<0.001$ were obtained, which is half as much as for the standard grease based on MoS_2 ($\mu\approx0.002$) and for graphite grease ($\mu\approx0.001$). As a physical mechanism that determines the characteristics of a lubricating film based on pyrolytic graphite intercalated with fullerenes, scientists consider the possibility of rolling of fullerene molecules on the graphite surface, which is characterized by much lower friction compared to the sliding of graphite surfaces relative to each other due to the higher contact area in the latter case It follows that fullerenes act as micro-rolling bearings that reduce the coefficient of friction. [10,11]. The limits of application of fullerenes are very wide. As far as lubricants are concerned, many additives for lubricating oils and greases are being developed on the basis of fullerenes. Recently, the production of lubricants based on fullerenes, which are characterized by extraordinary characteristics, is promising.

Formulation of the problem

The main lubrication units in turbojet aircraft engines are rolling bearings, in contrast to the lubrication units of piston engines in which sliding friction prevails. The temperature of the outer cage of such bearings reaches 125-150 °C, which is mainly created due to the heat coming from the turbine impeller. After the engine stops, when the air blowing decreases, the heat flow coming from the impeller heats the bearing bracket and the oil that lubricates it and removes heat from the friction zone to a temperature of 200 °C.

In turbojet engines of supersonic aircraft, the temperature in the friction nodes increases sharply both due to the increase in the load on the turbine bearings and due to the heat coming from the combustion chamber and the turbine impeller. At the same time, the temperature of the oil rises. In promising supersonic turbojet engines, the temperature in the friction nodes can reach 400 and even 540 °C, and the oil temperature up to 150-200 °C. For operation at such temperatures, liquid mineral oils are unsuitable, and synthetic oils must contain anti-wear and antioxidant additives, which performed b its functions under such conditions. Therefore, research aimed at obtaining and using new additives for lubricating materials that would work at high temperatures and significant loads is quite relevant.

Purpose and tasks

The purpose of the work was to study the possibilities of using and introducing new, promising complex additives to fuel and lubricant materials that will work for a longer period of time than traditional additives.

To improve the operational properties of fuels and lubricants - thermal oxidation stability of hydrocarbons, anti-wear characteristics, phenolic antioxidant additives - "ionol", anti-wear additives - "Hatec-580" are used, but at elevated temperatures they quickly oxidize. Therefore, the main task of this scientific work is the introduction of new, promising complex additives to fuel and lubricants based on nano-sized carbon materials (fullerenes), which are more resistant to the oxidation process, and the study of changes in the antiwear properties of lubricating materials under their influence.

To achieve the goal, the following tasks were solved:

- determination of tribological parameters of mineral MK-8п and synthetic Mobil Jet Oil 254 turbojet aircraft engine oils with C60 fullerene content on a standardized four-ball friction machine;
- studying the possibility and expediency of using fullerene additives in aviation mineral and synthetic oils.

Research materials and methodology

The development and introduction into operation of new lubricating oils with the aim of expanding the raw material base for their production and improving operational properties was carried out simultaneously with the development of engine construction. The large transmitted power of aviation gearboxes, in combination with their small weight and dimensions, leads to increased operating conditions of friction pairs, an increase in thermal and dynamic stress of engine parts and assemblies. Gears of reducers, as mentioned above, work under conditions of high contact loads. The strength of the films of low-viscosity aviation oils suitable for lubricating the supports of turbojet engines under these conditions is insufficient. To ensure reliable lubrication of the gears of the gearbox, oils with a higher viscosity and higher lubricating capacity are required.

Contradictions in the quality requirements of mineral oils, which must combine high lubricity with satisfactory viscosity-temperature characteristics to ensure reliable engine start-up at low temperatures, have led to the need to use a mixture of low-viscosity mineral oils for the lubrication of helicopter propeller gearboxes and turboprop engines (type "MK-8") with highly viscous residual oils "MC-20" (or "MK-22"). Moreover, the ratio of the indicated oils in the mixtures is different for different types of engines. An alternative solution to this contradiction is the use of Mobil Jet Oil 254 synthetic oil in the engine and gear system of Airbus Helicopters H-145 helicopters. Mobil Jet Oil 254 is an extremely high performance synthetic oil for third generation gas turbine engines, developed to meet their requirements and use in commercial and military aviation. This product is made from a specially formulated synthetic ester base oil and is enriched with an additive package. The oil has excellent thermal and oxidative stability, resisting degradation and scale formation while maintaining the physical characteristics required by manufacturer and military specifications. The physical properties of Mobil Jet Oil 254 are similar to the previous generation gas turbine lubricants currently available. The effective working range of the oil is from minus 40 °C to plus 230-250 °C. The viscosity of synthetic oils at temperatures of 250-300 °C is higher than that of mineral oils of equal viscosity at 100 °C, they have better thermal stability, low evaporation and low tendency to high-temperature deposits and foaming. Synthetic oils are superior to mineral oils in terms of antioxidant properties, and have equal or better anti-wear and anti-scratch properties. In this regard, their service life is several times longer than the service life of mineral oils. Recently, effective antifriction additives (friction modifiers) have been introduced into synthetic oils, which contribute to improving their performance in the high temperature zone and antiwear properties.

New synthetic materials, the operational characteristics of which are significantly superior to natural ones, are the basis of humanity's advancement along the path of progress. Fullerene is essentially a new form of carbon. The C60 molecule contains fragments with fivefold symmetry, which are not found in nature for inorganic compounds (Fig. 1). Therefore, it should be recognized that a fullerene molecule is an organic molecule, and a crystal formed by such molecules (fullerite) is a molecular crystal that is a connecting link between an organic and an inorganic substance. Each carbon atom in the C60 molecule is located at the vertices of two hexagons and one pentagon and does not fundamentally differ from other carbon atoms.

a b

Fig. 1. C60 fullerene molecule: a – general view; в – double bonds between carbon atoms

The carbon atoms that make up the sphere are bound together by a strong covalent bond. The thickness of the spherical shell is 0.1 nm, the radius of the C60 molecule is 0.357 nm. The length of the C – C bond in the pentagon is 0.143 nm, in the hexagon - 0.139 nm.

The C60 fullerene molecule maintains its thermal stability up to 1700 K, which is significantly higher than the temperature in the friction unit of the rolling bearing of the gas turbine of the helicopter engine or in its gearbox.

However, in the presence of oxygen, the oxidation of this form of carbon to CO and CO_2 is observed already at significantly lower temperatures (about 500 K). The process leads to the formation of an amorphous structure in which there are twelve oxygen atoms per C60 molecule, while the fullerene molecule almost completely loses its shape. When the temperature is further increased to 700 K, the intensive formation of CO and CO_2 and the final destruction of the ordered structures of fullerenes occur.

Of interest is the halogenation of fullerene, especially its fluorination. In the first works devoted to fullerene fluorides, the reaction of its interaction with gaseous fluorine was used, as a result of which a mixture of products was formed. The solubility of C60 fullerene itself in non-aromatic solvents is low, while its fluorides are quite soluble in hexane, chloroform, and acetone, and with aromatic compounds they form stable crystal solvates under normal conditions.

The research was conducted using MK-8 mineral aviation oil and Mobil Jet Oil 254 synthetic oil with additives of different fullerene content. Control of the content and solubility of C60 fullerene in olives was determined according to the method described in [9]. The investigated fullerene additives in different mass ratios of finely dispersed powder were added to the oil and mechanically mixed to a homogeneous suspension.

The quality of hydrocarbon lubricants is determined by their viscosity and anti-wear properties in the working temperature range. From a chemical point of view, these properties are provided, first of all, by the molecular weight and degree of branching of hydrocarbon chains. One of the main operational properties of oils is high resistance to oxidation and anti-wear properties.

To assess the effect of fullerene on the antiwear properties of oils, tribological tests were performed on a standardized four-ball friction machine in accordance with GOST 9490 (ASTM D2783) (Fig. 2).

According to the results of the research, wear was determined, which was estimated by the diameter of the wear spots d and the critical load Pk of the transition to seizure.

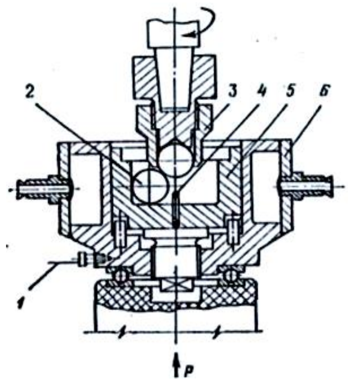


Fig. 2. Four-ball friction machine: 1 – screw; 2 – balls; 3 – friction node; 4 – acoustic probe; 5 – glass; 6 – housing

The three lower balls are fixed immovably in the cup of the machine with the lubricant being tested. The upper ball, which is fixed in the spindle of the machine, rotates relative to the three lower ones under a given load with a rotation frequency of 1460±70 rotate/m. Turning the balls during the test is not allowed.

Balls must be made of bearing steel ShKh-15 not lower than the II degree of accuracy, class B, with a diameter of 16 or 20 mm. It is possible to use balls from new real bearings for testing.

Antiwear properties on a four-ball friction machine are determined for oils and plastic lubricants used to lubricate friction surfaces.

The method consists in testing the lubricating material on a friction machine under specified axial loads and determining the main tribological characteristics of lubricating materials: bearing capacity - according to the critical load Pк, anti-seize properties according to the burr index - I_b, ultimate load capacity - according to the welding load Pz and anti-wear properties - according to diameter of wear spots (d).

Before starting the test of each sample of lubricant, all parts of the machine with which the lubricant comes into contact during the test (the cup with the parts of attachment of the lower balls and the parts of attachment of the upper ball) are washed with gasoline or benzene and dried in air. The balls used in the test are also washed with gasoline and air-dried.

Testing of each lubricating material is carried out at the temperatures established in the regulatory and technical documentation.

The test consists of a series of determinations. Each determination is carried out on a new sample of the tested lubricant with four new balls.

To conduct the test, the balls are fixed in the spindle of the machine and the cup for the lubricating material. When testing the oil, it is poured so that the balls are completely covered with it. Then a cup with lubricating material is installed in the machine, the load is set and the electric motor is turned on. In order to avoid deformation of the balls, it is necessary to avoid shock loads.

When conducting a test at elevated temperatures, the electric heater is previously turned on. After reaching the set temperature, create the necessary load and turn on the electric motor. The test temperature must be maintained with an error of no more than ±5°C.

The duration of the test from the moment of switching on to the moment of switching off the electric motor when determining the critical load, welding load and burr index should be 10 ± 0.2 s, when determining the wear rate - 60 ± 0.5 min.

When determining the critical load, which characterizes the ability of the lubricating material to prevent the occurrence of burr on the friction surfaces, a series of successive tests with a decrease or increase of the load are first carried out in accordance with a number of loads given in the test standard. Two parallel tests are conducted.

When welding, it is necessary to turn off the electric motor immediately to avoid damage to the machine.

The wear index, which characterizes the influence of the lubricant on the wear of the friction surfaces, is determined under the constant load established in the regulatory and technical documentation for the lubricant.Two parallel tests are conducted.After the end of the test and cooling of the friction assembly below 40 °C, drain the oil and wipe the balls with gasoline or alcohol.

Then measure the diameters of the wear spots of each of the three lower balls in the direction of sliding and perpendicular to it in a plane perpendicular to the axis of the microscope objective with an accuracy of 0.01 mm (Fig. 3).. The result of the measurement is taken as the average arithmetic value of the measurements of the wear spots of the lower balls in two directions.

The results of solving the main tasks of the problem and their discussion

The object of research of this work is the process of influence of nano-sized carbon materials (fullerene C_{60}) on anti-wear properties of mineral MK-8p and synthetic Mobil Jet Oil 254 oils of turbojet aircraft engines.

The subject of the study is the main tribological characteristics of aviation oils with additives of fullerene nano-sized carbon materials, determined according to the standard method on a four-ball friction machine.

The resource and reliability of engines largely depends on the extent to which the used aviation oil meets the operational requirements of its use. After the discovery of fullerenes, it became possible to create new lubricating materials. This possibility was indicated both by the ideal spherical shape of C60 fullerene molecules and by the base of these molecules (carbon), which in the form of graphite has long been widely used as an antifriction component of a whole class of lubricating materials. Numerous experiments conducted recently indicate increased lubricating characteristics of oils as a result of adding a small amount of fullerenes to them.

A characteristic feature of modern jet aircraft engines is the absence of sliding bearings. Rolling bearings are used as supports for the engine rotor shaft and aggregate drive shafts. The coefficient of rolling friction is in the range of 0.001-0.003 for ball bearings and 0.002-0.005 for roller bearings, while for sliding bearings this value is ten times greater (approximately 0.01). The rotors of modern aircraft engines are well balanced and, despite their high rotation speeds and considerable weight, the maximum radial load on the bearing does not exceed 1500 N. Anti-wear properties were studied using a four-ball friction machine according to ASTM D2783 according to the parameters of wear spot diameter (d) and critical load (Pk). The last indicator characterizes the maximum amount of load, at which metal contact (burrs) does not yet occur when rubbing standardized metal balls. When determining the limit wear indicator (d), the duration of the test from the moment of switching on to the moment of switching off the engine is 60 ± 0.5 min, under a standard load of 20 kg (196 N) and room temperature. In general, for each lubricating material, the test conditions are indicated in the regulatory and technical documentation. In this case, the same test conditions were chosen for mineral and synthetic oils for the convenience of comparing their properties.

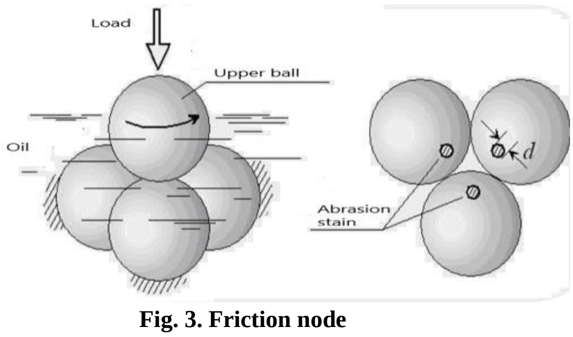


Fig. 3. Friction node

The dependence of the diameter of the wear spot on the concentration of the fullerene additive in mineral MK-8p and synthetic Mobil Jet Oil 254 aviation oils is shown in Fig. 4. As the research results showed, the increase in the concentration of the fullerene additive in oils does not significantly affect the amount of wear, although there is a tendency to decrease the diameter of the wear spot. It should also be noted that a more intensive reduction in wear is observed in mineral oil than in synthetic oil. The nature of this action of fullerene-containing additives has not yet been completely clarified.

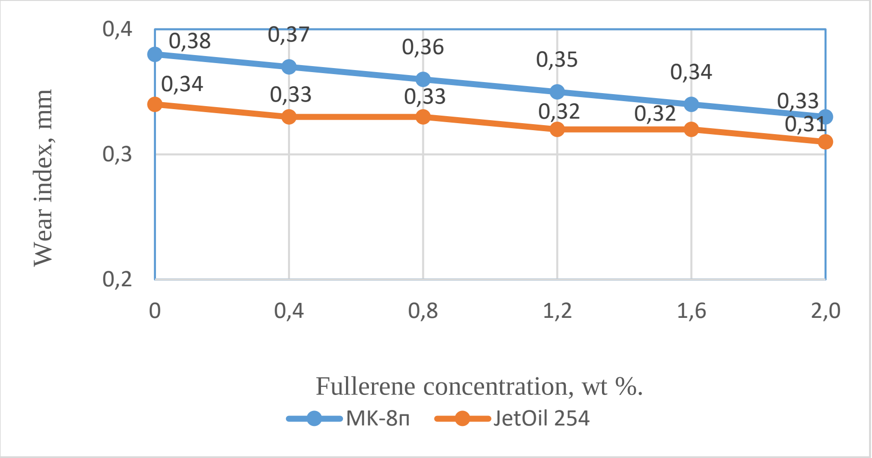


Fig. 4. Dependence of the wear index on the content of C60 fullerene in the oil

The critical load (Pk, kgf) is considered to be the load at which the average diameter of the wear spots of the lower balls is within the values of the limit wear value for this load, given in the ASTM D2783 table, the increase of which by the value of the next load in a series of loads causes an increase in the average diameter of the spots wear greater than 0.1 mm. The smaller value of the critical load from the two obtained values (Table 1 and Table 2) is accepted as the result of the test.

Table 1

Determination of critical load (Pk) for MK-8 oil

Load, kgf	Load, N	The average diameter of the wear spots of the lower balls, mm	Critical load, kgf
20	196	0.38	-
40	392	0.46	-
60	588	0.49	-
80	784	0.53	-
100	980	0.57	-
120	1176	0.61	-
160	1568	0.65	-
200	1960	0.82	($P_к$) 200

Table 2

Determination of critical load (Pk) for Mobil Jet Oil 254

Load, kgf	Load, N	The average diameter of the wear spots of the lower balls, mm	Critical load, kgf
20	196	0.36	-
40	392	0.41	-
60	588	0.45	-
80	784	0.51	-
100	980	0.54	-
120	1176	0.59	-
160	1568	0.61	-
200	1960	0.65	-
240	2352	0.68	-
280	2744	0.71	-
320	3136	0.89	$P_к$ (320)
360	3528	0.96	+

The critical load characterizes the beginning of the destruction of the lubricating film and the transition from a normal type of friction to an abnormal one, which is characterized by large wear of parts. From the above tables, it can be seen that the critical load for mineral oil MK-8 under the same test conditions is 1960 N, while for synthetic oil Mobil Jet Oil 254, the critical load is 3136 N. This can be explained by the fact that synthetic oil contains a package of additives that significantly improve its anti-wear properties, while mineral oil contains only one antioxidant additive.

The dependence of the critical load on the content of the fullerene additive in oils is shown in Fig. 5.

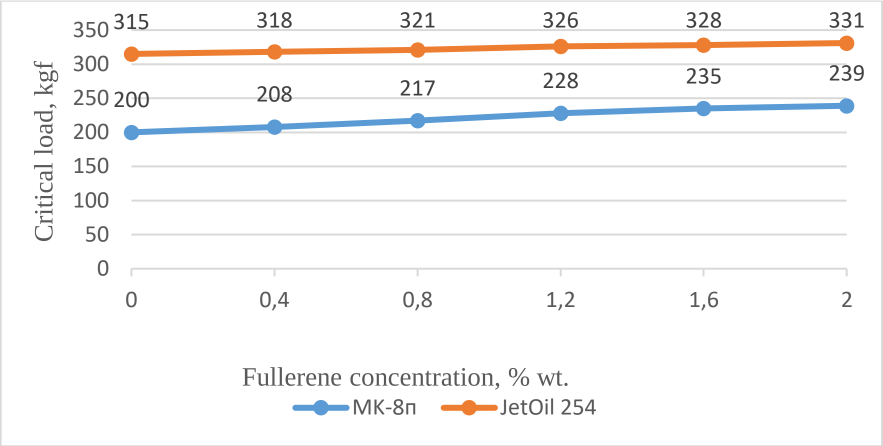


Fig. 5. Dependence of the critical load on the content of fullerene in the oil

Research results have shown that increasing the concentration of fullerene additives in oils shifts the critical load to higher values, both for mineral and synthetic oils. It should also be noted that the intensity of this growth in mineral oil is observed to a greater extent than in synthetic oil, possibly due to the effect of the additive package.

Based on the totality of the obtained results, it is possible to predict and predict the mechanism of antifriction and antiwear action of fullerenes as follows. In the process of tribopolymerization of mineral oil, a coating is formed on the friction surfaces in the form of a three-dimensional tribopolymer network connected to the substrate by chemical bonds.

This coating protects the rubbing surfaces from direct contact, and at the same time, being a spatial polymer mesh, retains the mineral oil, thus providing both a low-wear mode of friction and a low coefficient of friction. This process can occur without the presence of C60. However, without fullerene, the formation of a tribometallopolymer coating probably requires more time and more specific conditions. Due to its high reactivity, the presence of fullerene dramatically accelerates the tribopolymerization process and leads to the formation of a tribopolymer network, in the nodes of which there are mainly C60 molecules. This fundamentally changes the pattern of friction, as the tribopolymer protective coating in this case is implemented much faster and the low-wear and anti-friction mode of friction has time to be implemented before the destruction of the protective film. Finally, if in the process of friction the tribopolymer coating is disturbed (for example, under the influence of increased load) and there is a direct contact of the friction bodies, the process of tribopolymerization increases and the tribofilm is restored.

Therefore, tribocontact is a rather powerful reactor for various kinds of structural transformations, and one can expect the appearance in the friction zone of those fullerene modifications that have increased hardness and can determine the properties of surface films formed in the process of tribowear.

Conclusions

Fullerene nanoadditives are an effective means of increasing the tribological properties of oils of both mineral and synthetic origin. It was established that an increase in the concentration of the fullerene additive in olives up to 2% by weight. contributes to the growth of anti-wear properties of mineral oil MK-8p by 15%, synthetic oil Mobil Jet Oil 254 by 10%.

It was found that an increase in the concentration of the fullerene additive in oils shifts the critical load to higher values. At a content of 2% wt. fullerene critical load increases for mineral oil MK-8p by 19.5%, and for synthetic oil Mobil Jet Oil 254 by 5%.

A more positive effect of C60 fullerene additives on the tribological properties of mineral oil compared to synthetic oil was established: according to the indicator of the wear spot diameter - 1.5 times, according to the critical load indicator – 3.9 times, which is related to the difference in the oil base and the presence in a synthetic oil package of complex additives.

It was found that the anti-wear properties of synthetic oil Mobil Jet Oil 254 for turbojet aircraft engines exceed the indicator of MK-8p mineral oil by more than 10%, and the critical load - by 58%.

Scientific progress in this direction is mainly determined by experimental studies, the conduct of which is quite relevant.

References

1. Dmytrychenko N.F., Mnatsakanov R.G., Mikosyanchyk O.A., Kush A.I. Kinetics of wear of contact surfaces with the use of C60 fullerene additive to engine oil // Journal of Friction and Wear. - 2009, 30 (6), pp. 399-403.

2. Kuskova N.I. Tribological characteristics of nanocarbon materials. Electronic processing of materials, Mykolaiv, 2006, No. 6, pp. 50-56.

3. Valerii Yefymenko. Oxidative stability of lubricating materials with fulerene nanoadditives/ Valerii Yefymenko, Tetiana Kravchuk , Oleksandr Yefimenko// – К.: Вісник НАУ, №1, 2021. – P. 57 - 62. https://doi.org/10.18372/2306-1472.86.15445

4. Polunkin E.V., Kameneva T.M., Zhyla R.S. Peculiarities of the antioxidant action of exomodified fullerenes C60 at the oxidation of organic compounds // The International research and practice conference “NANOTECHNOLOGY AND NANOMATERIALS (NANO-2017)”, 23-26 August 2017, Chernivtsi. - P. 778.

5. Pat. 23255 Ukraine, IPC C 10 N 10/00. Kovtun G.O., Pluzhnikov V.O., Zhila R.S. etc. Fullerene C60 - antioxidant additive to lubricating oils. Publ. 10.05.2007.

6. Mykhaylenko O. V. Fullerenes, nanotubes and nanorings: – stereochemistry and method of coding (nomenclature). Complexes of fullerenes with calixarenes. Diss. Ph.D. chemical Sciences, Kyiv. - 2005. - 137 p.

7. Vicens J. Calixarenes in the Nanoworld / J. Vicens, J. Harrowfield. - Dordrecht: Springer, 2007. - 395 p.

8. Kovtun G.A. Fullerene C60 in the breakdown of oxidation chains of organic compounds / G.A. Kovtun, T.M. Kameneva, R.O. Kochkanyan // Catalysis and petroleum chemistry. – 2003. – No. 11. - C. 36-38.

9. Yefimenko V.V., Yefimenko O.V., Kalmykova N.G. Control and determination of the concentration of fullerene additives in hydrocarbon liquids // XV International Scientific and Technical. conf. "Avia-2021", April 20-21, 2021. theses add. - K.: NAU, 2021. - P.19.10-19.13. // http://conference.nau.edu.ua/index.php/AVIA/AVIA2021/paper/view/8308/6860.

10. Podcherniaeva I. A., Yurechko D. V., Panashenko V. M. Some development trends in the development of wear-resistant functional coatings // Powder metallurgy and metal ceramics. - 2013. - T. 52. - no. 3-4. - WITH . 176-188.

11. Achanta, S., Selis, J.P. (2007). MEMS/NEMS nanotribology. In: Gnecco, E., Meyer, E. (eds.) Fundamentals of Friction and Wear. Nanoscience and technology. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-36807-6_23

Олександренко В.П., Єфименко В.В.. Калмикова Н.Г., Єфіменко О.В., Будяк Р.В., Нелюбін Ю.М. Протизносні властивості змащувальних матеріалів з фулереновими наноприсадками

Метою даної статті є дослідження можливості застосування фулеренових присадок та їх впливу на протизносні властивості авіаційних мінеральних та синтетичних олив. Розглянуто метод підвищення протизносних властивостей мінеральної МК-8п та синтетичної Mobil Jet Oil 254 олив для турбореактивних авіаційних двигунів шляхом добавки фулеренової присадки C_{60}. Показано, що протизносні властивості синтетичної Mobil Jet Oil 254 оливи для турбореактивних авіаційних двигунів перевищують понад 10 % мінеральну оливу МК-8п. Збільшення концентрації фулеренової присадки в оливах підвищує зносостійкість спряжених поверхонь. Встановлено, що зростання концентрації фулеренової присадки в оливах зміщує критичне навантаження в область більш високих значень як для мінеральної, так і для синтетичної оливи. Інтенсивність цього зростання в мінеральній оливі спостерігається в більшій мірі, ніж у синтетичній оливі.

Запропоновано використання фулеренів в якості протизносної присадки до олив для турбореактивних двигунів, що поліпшує антифрикційні властивості та зменшує знос деталей машин і механізмів. Науковий прогрес визначається в основному експериментальними дослідженнями, проведення яких в даному напрямку є досить актуальними.

Ключові слова: фулеренові присадки, мінеральна олива, синтетична олива, чотирьохкулькова машина тертя, показник зносу, критичне навантаження.

Problems of Tribology, V. 28, No 2/108-2023, 37-43

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-37-43

Features of Increasing the Wear Resistance of Machine Parts by Treatment with a Concentrated Heat Flow

Iu. Sokolan*, O. Romanishina, K. Sokolan, P. Maidan, V. Karazey

Khmelnitskyi National University, Ukraine
**E-mail:sokolanjulia@gmail.com*

Received: 21 April 2023: Revised:17 May 2023: Accept:31 May 2023

Abstract

The article discusses the possibility of using surface treatment of parts with a concentrated heat flow to increase the wear resistance of parts. This method provides conditions for the rapid crystallization of the metal structure after zonal surface melting of the sample surface with electric arc plasma. It has been found that the wear resistance of steel increases significantly with increasing scanning speed and decreasing current strength. The near-surface layers on the cross-sectional grinds of the melting areas were studied in comparison with the initial (without melting) state on the basis of diagrams of the method of continuous indenter immersion. The values of a number of micromechanical parameters characterizing the resistance to microplastic deformation and elastic-viscous properties of steel after strengthening heat treatment were obtained. It should be noted that with a fourfold increase in hardness, the wear resistance of the steel increased almost 10 times. This indicates that the wear resistance of metals under friction is determined not only by macroscopic strength and hardness, but also by the ability to relax local peak stresses under dynamic contact interaction.

Key words: GTAW method, surface hardening, wear resistance of steel, electric arc treatment, concentrated heat flux.

Statement of the problem

Heat treatment of working surfaces of machine parts with the use of concentrated heat flow of high power allows to solve technical problems associated with increasing the wear resistance of metal products. In this regard, from the economic point of view and technological capabilities, the electric arc plasma treatment method is of interest, allowing after surface melting to cause rapid crystallization of metal due to intensive heat transfer (GTAW method) [1]. However, the influence of technological parameters of the melting process with subsequent recrystallization of the metal on the forming microstructure and its rheological strength properties, determining the wear resistance, remains insufficiently studied.

Analysis of the available investigations

GTAW (Gas-Tungsten-Arc-Welding) has become one of the most common arc welding methods. This is due to the fact that the resulting welds are characterized by high quality. One of the main advantages of this technology is the possibility to weld a wide variety of materials: along with low-carbon, high-alloy and martensitic steels, more valuable is the possibility of high-quality welding of aluminum and magnesium alloys, and in addition, such metals and alloys as titanium, zirconium, molybdenum, nickel, copper, bronze, brass [2, 3].

Nevertheless, the works devoted to the application of this method do not consider its use as one of the possible methods of surface hardening of machine parts, which in the future will be subjected to friction conditions without lubrication. In this regard, the question of the possibility of applying the GTAW method as a method of pre-treatment of materials is relevant.

The Objective of the work

Evaluate the effectiveness of surface heat treatment of steel with electric arc plasma to improve tribological parameters.

Statement of the task

GTAW (Gas-Tungsten-Arc-Welding) method was used for surface hardening, which provides conditions of fast crystallization of metal structure after zonal surface melting by electric arc plasma of sample surface in the form of tiles (200 × 50 × 10 mm). The basis of the experimental setup was equipment FALTIG 315AC/DC with protective gas (argon) and the use of non-consumable tungsten electrode (diameter 2.4 mm), hardened by thorium oxide. Installation scheme and general view are shown in Fig. 1 and 2.

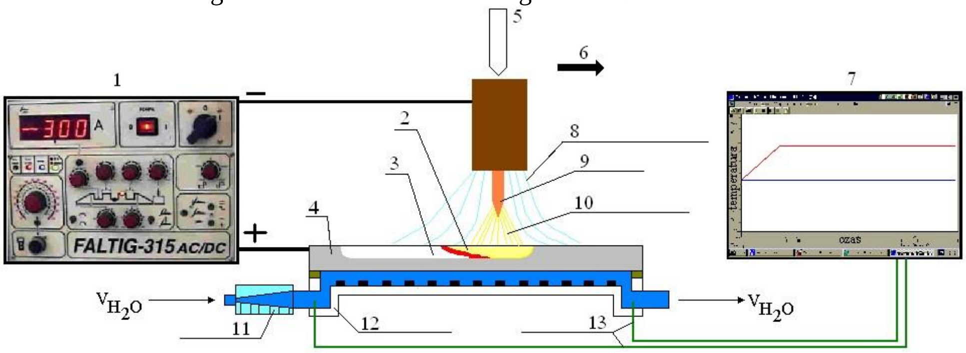


Fig. 1. Schematic of the installation for melting and calorimetric studies (method GTAW: Gas-Tungsten-Arc-Welding): 1 - current source, 2 - liquid metal welding bath, 3 - melted layer, 4 - sample, 5 - protective gas, 6 - direction of arc movement, 7 - temperature gauge, 8 - protective atmosphere, 9 - electrode, 10 - electric arc, 11 - flow meter, 12 – calorimeter, 13 – thermocouple

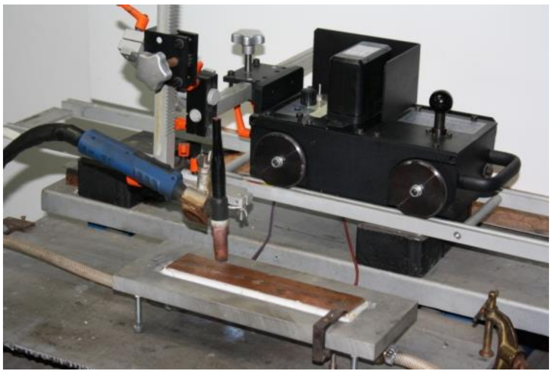


Fig. 2. General view of the installation

To intensify heat removal and accelerate crystallization, the sample tile was fixed as a flow calorimeter cover so that its lower plane was cooled by a water flow, while its upper surface was zonally melted. During arc scanning, the temperature of water at the inlet and outlet of the calorimeter was measured at the set water flow [4]. The heat absorbed by the tile material is spent for heating (Q_H) and melting ($Q_П$) of the scanning zone. The amount of heat absorbed in this way (taken by the calorimeter) was calculated by the formula:

$$Q_k = Q_H + Q_П = \rho \cdot V \cdot c \cdot \Delta t, \quad (1)$$

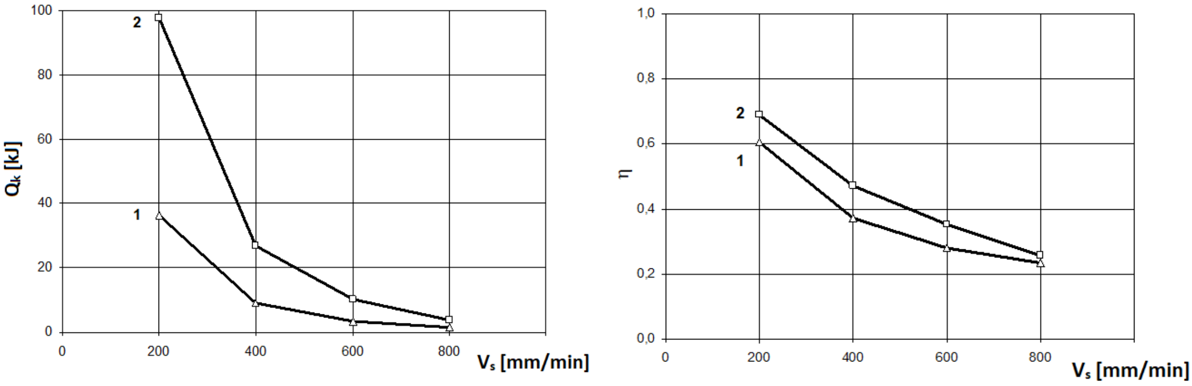
where ρ is the density of water; V is the volume of water consumed in the fusion process; c is the specific heat capacity of water; Δt is the temperature increase of water.

The efficiency of useful use of the heat released in the electric arc was evaluated by the thermal efficiency:

$$\eta = Q_k/Q, \quad (2)$$

where $Q = I \cdot U \cdot \tau$ is the total amount of heat released during time τ.

The influence of the main process parameters of the GTAW process (current strength and arc scanning speed) on the amount of heat taken by the tile sample during heating and melting ($Q_k = Q_H + Q_П$), as well as the effect on the thermal efficiency of the process η (Fig. 3) were studied. The arc voltage was of secondary importance.

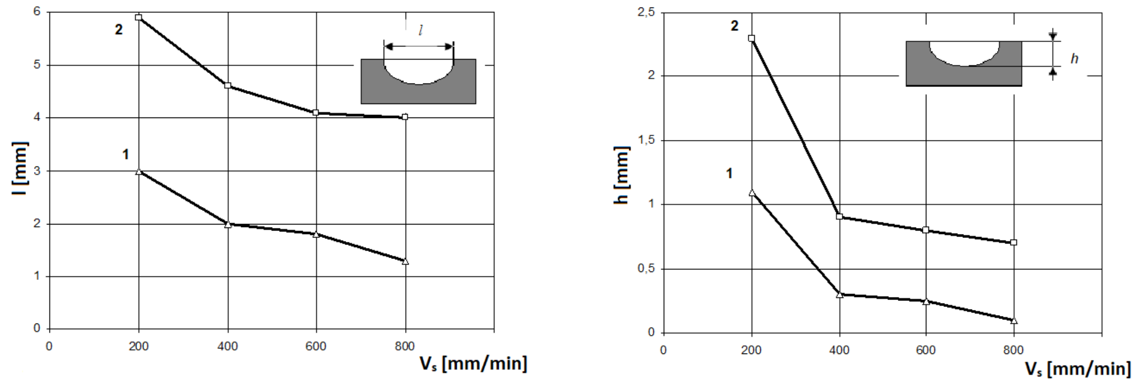


a b

Fig. 3. Dependence of the absorbed amount of heat Q_k (a) and thermal efficiency. η (b) as a function of arc scanning speed and current strength: 1 - I = 100 A; 2 - I = 200 A (U = 14 V)

The dependences obtained show that the efficiency of heat reception by the sample increases with increasing current strength and decreasing scanning speed. In the investigated range, the highest values of thermal efficiency. (η = 60 ÷ 70 %) were observed at the speed V_s = 200 mm/min.

Fig. 4 illustrates the influence of the studied technological parameters on the geometric parameters of steel sample melting. It can be seen that the width, depth and cross-sectional area of the melts increase with increasing current and with decreasing scanning speed. These geometrical characteristics are more sensitive to current variations at low scanning speeds. The values of Q_k and η, affecting the values of l and h, simultaneously form the temperature-rate parameters of the thermal cycle: heating - melting - crystallization - hardening - self-tempering of steel. The decisive factor influencing the formation of steel structure is the rate of heat removal from the melting zone.



a b

Fig. 4. Influence of current strength and scanning speed of electric arc on the width l (a) and depth h (b) of melting: 1 - I = 100 A; 2 - I = 200 A

Effect of electric arc treatment on the wear resistance of steel. Pre-eutectoid low-carbon steel 20 was investigated. The anti-wear properties of steel were determined by testing cube-shaped specimens (10 × 10 × 10 mm), which were cut from the fusion zones. In a friction machine, such a specimen was pressed with a controlled force against the surface of a 210 mm diameter rotating disc made of white cast iron (60 HRC). The specific load was Pn = 1 MPa, the sliding speed (without lubrication) V_t = 1.6 m/s, and the test time 2 hours. The wear intensity was calculated according to the formula:

$$Z = \frac{\Delta m}{\rho \cdot A \cdot L}, \quad (3)$$

where Δm is sample mass loss; ρ is steel density; A is contact area; L is friction path.

The comparison of steel wear resistance depending on the parameters of melting - current and scanning speed was carried out (Fig. 5). It was found that the wear resistance of steel increases significantly with increasing scanning speed and with decreasing current. Thus, after melting at a scanning speed of 800 mm/min and a current strength of 100 A, the intensity of wear decreases almost by one order of magnitude. This testifies to the fact that the increased scanning speed and reduced current contribute to such optimization of cooling and crystallization conditions, under which the microstructure with favorable strength and viscoelastic properties is formed.

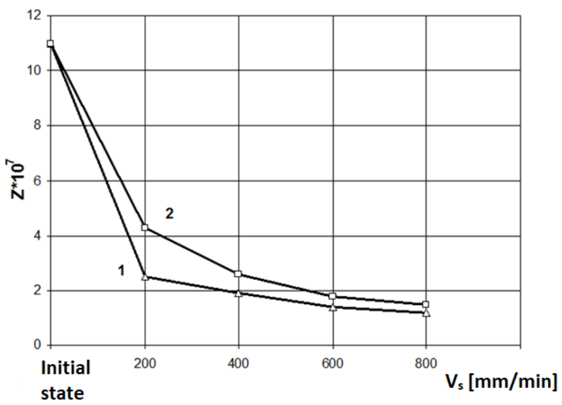
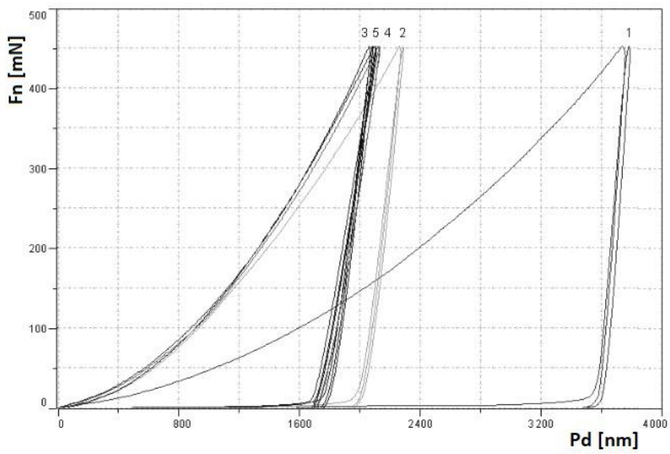


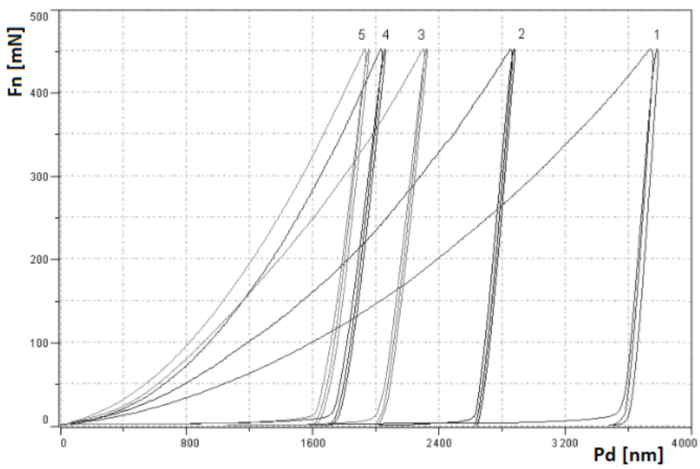
Fig. 5. Dependence of steel wear rate on electric arc scanning speed (Fn = 1 MPa, V_t = 1.6 m/s): 1 - I =100 A; 2 - I =200 A

The micromechanical and rheological properties of the surface layers were evaluated using the parameters of kinetic diagrams of continuous indentation of a Berkovich indenter on the NHT/NST unit of CSM Instruments (Switzerland) [5-7]. Double loading-unloading cycles with registration of the dependence of the indenter penetration depth (P_d) on the acting force (F_n) were investigated. At the same time the following were determined: microhardness $HV_{0,05}$, Young's modulus E, relaxation capacity R (relation of work of elastic aftereffects to the full work of indenter penetration), contact hardness S and hysteresis loop area W_H characterizing mechanical losses (cyclic viscosity) under repeated loading. The contact stiffness S is determined by the value of force reduction during indentor unloading per unit of deformation. The smaller the value of S, the more microplastic the material is.

Fig. 6 shows diagrams of tests of the materials under study by continuous indentation (two cycles of loading). The near-surface layers (at a depth of h = 50 μm) on the cross-sectional thin sections of the melting areas were investigated in comparison with the initial (without melting) state.



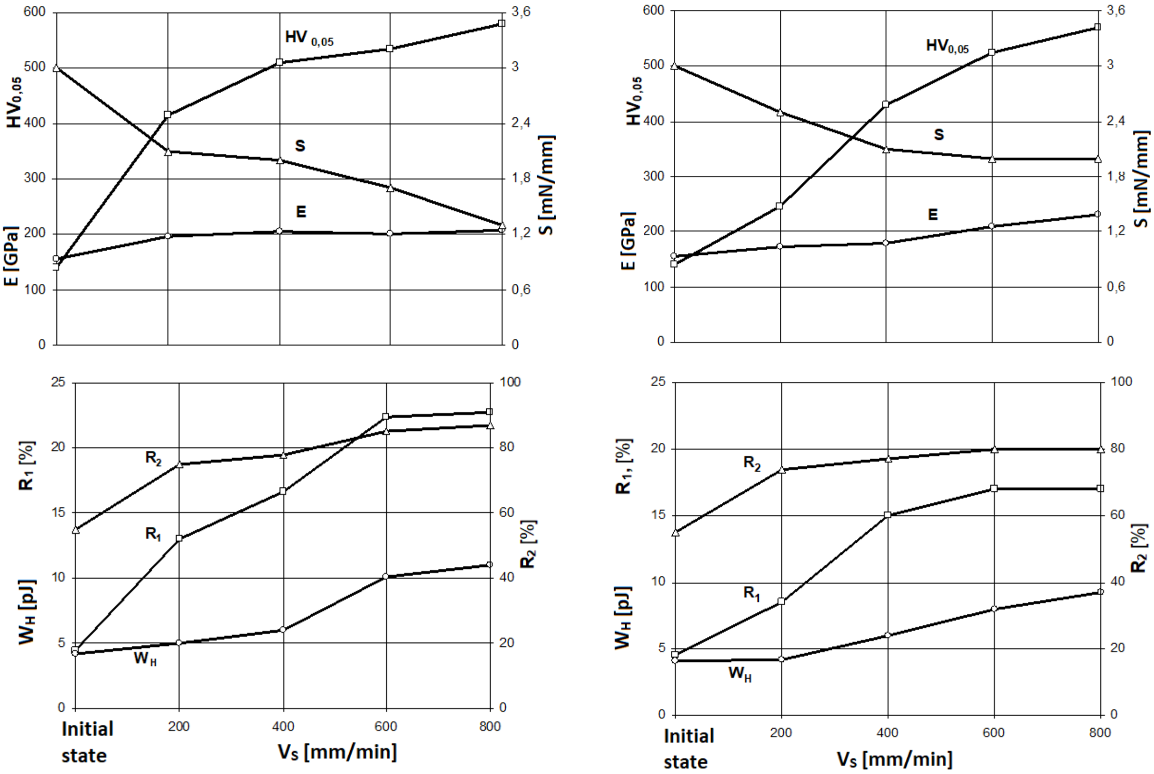
a



b

Fig. 6. Kinetic diagrams of continuous indenter microindentation after melting at arc current I = 100 A (a) and I = 200 A (b): 1 - initial state; 2 - 5 - V_S = 200, 400, 600, 800 mm/min

On the basis of recording of such diagrams the values of a number of micromechanical indices characterizing the resistance to microplastic deformation and elastic properties of steel after hardening treatment have been obtained (Fig. 7). A specific regularity is revealed: with increasing scanning speed during melting and subsequent rapid crystallization microhardness ($HV_{0,05}$), elasticity (E), relaxation indices (R_1, R_2) and dissipative capacity (hysteresis loop area WH) increase significantly. At the same time, the stiffness of the contact interaction between the indenter and the material (S) decreases. For clarity of comparison, these characteristics are summarized in Table 1 for scanning speed V_S = 800 mm/min.



a b

Fig. 7. Effect of arc scanning speed on the micromechanical properties of hardened surfaces at I = 100 A (a) and I = 200 A (b): $HV_{0,05}$ – microhardness; E – Young's modulus of elasticity; S – contact rigidity; R_1 and R_2 – relaxation capacity in the first and second cycles; W_H – hysteresis loop area

Table 1

Comparison of micromechanical parameters (Vs = 800 mm/min)

State of the material	Microhardness, $HV_{0,05}$	Modulus of elasticity E, GPa	Relaxation capacity		Hysteresis loop area $W_H \cdot 10^{-3}$, pJ	Contact rigidity S, mN/nm
			R_1, %	R_2, %		
Initial	140	155	4,5	55	4	3,1
Hardened at I = 100 A	580	205	23	87	11	1,4
Hardened at I = 200 A	570	230	17	78	9	2,0

From the above data it follows that the technology under study gives a 4-fold increase in hardness, 1.3 - 1.5 times increase in modulus of elasticity, 4 - 5 times increase in relaxation capacity, 2 - 3 times increase in dissipative capacity (cyclic viscosity) with a simultaneous reduction of contact stiffness in 1.5 - 2 times.

Conclusions

1. Optimized surface hardening process by electric arc plasma treatment (GTAW method) in terms of current strength and arc scanning speed, providing favorable conditions for rapid crystallization of zonally melted metal.

2. Surface melting of low-carbon steel by electric arc followed by rapid crystallization forms a vidmanstetted ferrite structure with a bainite strengthening phase. Such material at high hardness exhibits improved viscoelastic and relaxation properties, which provides a significant increase in wear resistance. In high-carbon bainite friction, unlike ferrite-perlite structures, the contribution of relaxation processes prevails over sticking during surface deformation. Therefore, martensite is additionally hardened by passing into a more ductile state and preserving high relaxation properties that ensure the development of non-damaging dissipative processes.

References

1.Orlovitch A. V. Surface hardening of cast iron by electric arc plasma / A. V. Orlovitch, A. S. Trytek, V. V. Shevelya. - Kyiv-Khmelnitsky, 2008. - 109 p. [In Russian]

2.Howard B. Cary, Scott C. Helzer. Modern Welding Technology. - Upper Saddle River, New Jersey: Pearson Education. – 2005. – 715 p. [In English]

3.Larry Jeffus. Welding: Principles and applications. - Thomson Delmar, 1997. – 901 p. [In English]

4.Shevelya V. V. Influence of electric arc treatment on structure and wear resistance of cast iron / V. V. Shevelya, A. S. Trytek, G. S. Kalda. // Problems of tribology. - 2009, - № 2. - p. 6-15. [In Russian]

5.Bulychev S. I. Testing of materials by continuous indentation / S. I. Bulychev, V. P. Alekhin. - Moscow: Mashinostroenie, 1990. – 224 p. [In Russian]

6.Bulychev S. I. Research of mechanical properties of materials with the help of kinetic diagram of load-depth imprint at micro-pressing / S. I. Bulychev, V. P. Alekhin. // Problems of Strength. - 1976. - № 9. - p. 79-83. [In Russian]

7.Bulychev S. I. Research of physical and mechanical properties of materials in near-surface layers and in micro-volumes by method of continuous indentation (review) / S. I. Bulychev, V. P. Alekhin, M. Kh. // Physics and Chemistry of Materials Processing. - 1979, № 5. - p. 69-81. [In Russian]

Соколан Ю., Романішина О., Соколан К., Майдан П., Каразей В. Особливості підвищення зносостійкості деталей машин шляхом обробки концентрованим тепловим потоком

В статті розглядається можливість використання поверхневої обробки деталей концентрованим тепловим потоком з метою підвищення зносостійкості деталей. Цей метод забезпечує умови швидкої кристалізації структури металу після зонального поверхневого оплавлення електродуговою плазмою поверхні зразків. Встановлено, що зносостійкість сталі значно зростає зі збільшенням швидкості сканування та зі зменшенням сили струму. Досліджувались приповерхневі шари на шліфах поперечного перерізу областей оплавлення порівняно з вихідним (без оплавлення) станом на основі діаграм метода безперервного занурення індентора. Отримані значення ряду мікромеханічних показників, що характеризують опір мікропластичній деформації та пружнов'язкі властивості сталі після зміцнювальної теплової обробки. Слід зауважити, що при чотирикратному підвищенні твердості, зносостійкість сталі збільшилась майже у 10 разів. Це свідчить про те, що опір зношуванню металів при терті визначається не тільки макроскопічною міцністю та твердістю, але й здатністю до релаксації локальних пікових напружень в умовах динамічної контактної взаємодії.

Ключові слова: метод GTAW, поверхневе зміцнення, зносостійкість сталі, електродугова обробка, концентрований тепловий потік.

Problems of Tribology, *V. 28, No 2/108-2023, 44-55*

Problems of Tribology

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

E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-44-55

Mathematical model of running-in of tribosystems under conditions of boundary lubrication. Part 2. Simulation results

A.V. Voitov

State biotechnological university, Kharkiv, Ukraine

E-mail: K1kavoitov@gmail.com

Received: 05 May 2023: Revised:27 May 2023: Accept:08 June 2023

Abstract

The paper presents the results of mathematical modeling of tribosystems running-in processes when various factors are changed: design parameters of tribosystems, which are taken into account by the form factor; tribological properties of the lubricating medium; rheological properties of composite materials in the tribosystem; roughness of friction surfaces; load and sliding speed. By comparing the theoretically obtained results, by modeling according to the developed models, with experimental data, it was established that the mathematical model adequately reflects the running-in processes taking into account the changes in constructive, technological and operational factors. Applying the Cochrane criterion, it was established that the obtained experimental results are homogeneous and reproducible. The maximum value of the coefficient of variation of the values of the volumetric wear rate and the coefficient of friction is within the limits v = 12,3 - 26,5%. The value of the simulation error is within the limits v = 7,7 - 12,9%.

A rating of factors that maximally affect the processes of running-in of tribosystems in the conditions of extreme lubrication has been obtained. In the first place is the roughness of the friction surfaces, the coefficient of variation v = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation v = 20,8%. In third place is the value of sliding speed during running-in, the coefficient of variation v = 18,6%. The conclusion made must be taken into account when developing a rational program for running-in tribosystems in conditions of extreme lubrication.

The methodical approach of applying the acoustic emission method in the study of tribosystem running-in processes is presented. It is proved in the work that in order to determine the volume rate of wear during tribosystem running-in, it is necessary to register and analyze the fourth cluster from the general acoustic emission signal. The sources of signal generation of the fourth cluster are microcutting and plastic deformation of protrusions of the roughness of the friction surface, which is characteristic of the first stages of running-in.

Key words: tribosystem; practice; mathematical model of training; marginal lubrication; form factor; tribological properties of the lubricating medium; rheological properties of composite materials; wear rate; coefficient of friction

Introduction

To date, in the literature there are many definitions of the process of running tribosystems. Running-in is a non-stationary initial transient process of friction in tribosystems, which results in adaptation of the contacting surfaces and a gradual transition to a stationary process by reducing and stabilizing the values of wear rate, friction coefficient and temperature. It should be noted that even with minor changes in loading conditions, lubricating medium or other friction conditions, the running-in surfaces will go through the stage of repeated (secondary) running-in. The surfaces of tribosystems will adapt to new working conditions.

The most effective tool for studying the running-in processes of tribosystems is mathematical modeling. A large number of mathematical models of such processes have been developed, but their application is limited for the following reasons. Firstly, a large error in modeling the parameters of the running-in process, for example, wear per run-in, run-in completion time. Secondly, the presence of an oscillatory process of wear rate and friction coefficient during running-in. The instability of such parameters reduces the adequacy of the developed models to experimental data, increases the simulation error. There is an opinion among researchers that the running-in of tribosystems has an individual trajectory and depends on design, technological and operational factors. In our opinion, it is this triad of factors that should be taken into account when developing models and modeling the processes of running-in of tribosystems.

Literature review

Authors of the work [1] note that running-in plays an important role in the further operation of machines. This is a transient process involving a complex interaction between friction, lubrication, surface roughness, plastic deformation, and run-in wear. The running-in process involves changing key tribological parameters such as surface roughness, coefficient of friction and wear rate, which tend towards a steady state. This article provides a comprehensive review of the literature on the subject, covering both experimental and analytical developments to date.

In work [2] it is proposed to represent the running-in process of the tribosystem as a time series of friction coefficients and the corresponding attractors. Due to the complexity and nonlinearity of tribosystems, friction attractors exist in multidimensional phase spaces. This makes it possible to visualize the phase trajectory of a complex running-in process. The authors compared and analyzed three methods for visualizing multidimensional datasets. Differences in the results of identification between the temporal and phase-spatial regions are shown. which indicates that recognition of the state of run-in results based on friction-induced attractors is more accurate.

According to the authors of the work [3] the quality of the running-in can be improved by optimizing the process parameters (load, sliding speed and running-in time). The authors analyzed the relationship between the quality of running-in and the parameters that affect the running-in. Based on the analysis, it was concluded that the principles for choosing the running-in parameters for various designs of tribosystems differ. The processing steps are also different. The authors of the work do not provide systemic recommendations on the choice of running-in stages and running-in parameters at these stages. However, it is positive, in our opinion, that the running-in process should be divided into stages and have different optimal parameters for each stage.

Authors of the work [4] note that numerical simulation is a powerful tool for estimating running-in wear. The modeling of the surface topography is taken into account in the form of contact pressure curves on the roughness ridges and, accordingly, wear values dependent on the contact pressure. To confirm the simulation results, the authors present the results of the experiment. It has been experimentally confirmed that taking into account the surface topography is a significant factor influencing the running-in process. A similar approach was used by the authors of the works [5, 6], where the significant factors are the surface roughness parameters [5], contact pressure [6].

In work [7] it is noted that the running-in of tribosystems must be performed at different loads and different sliding speeds. The authors of the work showed that the use of a multi-stage process in the running-in process reduces the running-in time and improves its quality. The authors present simulation results that allow making predictions on the choice of running-in modes.

A similar approach is presented in the work [8]. The authors developed and substantiated the structure of the tribosystems running-in program, which consists of two modes. The first mode is called the adaptation of the tribosystem to external conditions. The second mode is called the trainability and trainability of the tribosystem. The paper presents the transient characteristics of the running-in of tribosystems, which make it possible to establish the relationship between the design of the tribosystem, rational loading modes, running-in time and wear for running-in. The practical significance of the work is to minimize the running-in time and wear during the running-in period.

In work [9] the methodical approach was further developed in obtaining mathematical models that describe the running-in of tribosystems under boundary lubrication conditions. The structural and parametric identification of the tribosystem as an object of simulation of running-in under conditions of extreme lubrication was carried out. It has been established that the processes of running-in of tribosystems are described by a second-order differential equation and, unlike the known ones, take into account the limit of loss of stability (robustness reserve) of tribosystems. It is shown that the processes of running-in of tribosystems depend on the type of the magnitude of the input influence on the tribosystem, the first and second derivatives. This allows us to state that the running-in processes of the tribosystem will effectively take place when the input action (load and sliding speed) will change in time and have fluctuations with positive and negative acceleration of these values from the set (program) value. This requirement corresponds to the running-in program "at the border of seizing".

Summing up the analysis of works devoted to the processes of running-in modeling, we can make a platoon about the inconsistency of opinions about the choice of significant factors affecting the process. A reasonable choice and ranking of factors, according to their degree of importance, will allow to justify the running-in regimes and reduce wear during running-in and running-in time. The following are subject to study as significant factors: the design of the tribosystem; lubricating medium; the structure of conjugated materials in the tribosystem; roughness of friction surfaces; load and sliding speed. This article is a continuation of the work [9], where the mathematical model of the running-in process was obtained. The ranking of factors will allow us to develop a program for the effective running-in of various designs of tribosystems, which will be a continuation of this work.

Purpose

The purpose of this study is to simulate the running-in processes of various designs of tribosystems, experimentally determine the simulation error and build a rating of factors that affect the running-in efficiency.

Methods

In work **[9]** structural and parametric identification of the tribosystem as an object of simulation of run-in under conditions of extreme lubrication. It has been established that the processes of running-in of tribosystems are described by a second-order differential equation and, unlike the known ones, take into account the limit of loss of stability (robustness reserve) of tribosystems.

Modeling the running-in process depends on the following values:

- input impact on the tribosystem W_i, (the power supplied to the tribosystem) is determined by the formula given in the work [10];
- the maximum value of the input impact, when there is accelerated wear of tribosystem materials, or burr of friction surfaces, W_b, is determined by the formula given in the work [10];
- speed of dissipation in the tribosystem W_{TR}, is determined by the formula given in the work [10];
- the maximum value of the Q-factor of the tribosystem Q_{max} during the run-in time, is determined by the formula given in the work [11];
- the design parameters of the tribosystem are taken into account by the form factor K_f, is determined by the formula given in the work [11];
- given value of the coefficient of thermal conductivity of triboelement materials a_{red}, is determined by the formula given in the work [11];
- rheological properties of the structure of composite materials in the tribosystem RS_{TS}, is determined by the formula given in the work [11].

The solution for the given in the work [9] of the differential equation when modeling the volumetric rate of wear, there is the following expression:

$$I(t) = I_{st}\left[1 + (K_0 \cdot K_2)^{\lambda}(t) \cdot e^{\left(-\frac{d_I}{0{,}3 \cdot T_I} \cdot t\right)} \cdot (\cos \upsilon_I t + A_I \sin \upsilon_I t)\right], \quad (1)$$

where I_{st} – the value of the wear rate of the tribosystem after running-in (stationary mode) is determined by the expression given in the work [12].

The solution for the given in the work [9] of the differential equation when modeling the friction coefficient has the following expression:

$$f(t) = f_{st}\left[1 - (K_0 \cdot K_2)^{\lambda}(t) \cdot e^{\left(-\frac{d_f}{0{,}3 \cdot T_f} \cdot t\right)} \cdot (\cos \upsilon_f t + A_f \sin \upsilon_f t)\right], \quad (2)$$

where f_{st} – the value of the friction coefficient of the tribosystem after running-in (stationary mode) is determined by the expression given in the work [12];

K_0 and K_2 – gain coefficients are calculated according to the formulas given in the works [9, 13];

λ – exponent, which takes into account the change in the constant T_3, as a function of run-in time, a dimensionless quantity, is calculated according to the formula given in the paper [9];

t – run-in time, which varies from zero to completion of the run-in process, dimension second;

d_I and d_f - decrements of damping of oscillations during run-in for modeling the volumetric rate of wear and friction coefficient, the formulas for calculation are given in the work [9];

T_I and T_f - time constants of the tribosystem for modeling the volumetric rate of wear during run-in and the friction coefficient, the formulas for calculation are given in the work [9];

υ_I and υ_f - frequency of oscillations for modeling the volume rate of wear during run-in and the coefficient of friction, the formulas for calculation are given in the work [9];

A_I and A_f - the amount of deviation of the volume rate of wear from the current value during the oscillating process for modeling the volume rate of wear during run-in and the coefficient of friction, the formulas for calculation are given in the work [9].

Results

Applying formulas (1) and (2), we will simulate the processes of running-in of tribosystems over time when the following input factors are changed:

- geometric dimensions of the tribosystem, which are taken into account by the form factor K_f, 1/m;
- tribological properties of the lubricating medium E_u, J/m^3;
- rheological properties of the structure of combined materials in the tribosystem RS_{TS}, 1/m;
- roughness of friction surfaces *Ra*, m;
- load, N;
- sliding speed, m/s.

To use the developed mathematical model of the running-in of tribosystems, it is necessary to evaluate the reproducibility and adequacy of the results obtained theoretically and experimentally, as well as the modeling error.

To determine the rate of wear in the process of running in tribosystems (in online mode), we will use the conclusions of the work [14]. The purpose of this study is to develop a methodology for diagnosing various structures of tribosystems with the justification of informative frequencies and amplitudes when recording acoustic emission (AE) signals from the friction zone. In the paper, it is proved that in order to determine the volumetric rate of wear during tribosystem running-in, it is necessary to register and analyze the fourth cluster from the general acoustic emission signal.

The fourth cluster is a packet of AE signals, which is characterized by emissions of large amplitudes, the value of which exceeds the average value of the amplitudes of the first (basic) cluster *K1* in 3.91 ... 4.6 times. Sources of cluster signal generation *K4* are: microcutting and plastic deformation of protrusions of friction surface roughness, which is characteristic of the first stages of running-in.

In work [14] the sequence in the construction of the method of diagnosing tribosystems during running-in is formulated.

1. From the analysis of the design documentation, the materials from which the triboelements are made are determined (modulus of elasticity and Poisson's ratio), as well as the roughness parameters of the friction surfaces (*Ra*, *Sm*) and the value of the smaller friction area of one of the triboelements F_{min}.
2. From the analysis of operating conditions, the operating mode of the tribosystem is determined (load and sliding speed).
3. According to the formulas given in [14], the rate of deformation of the triboelement material and the informative frequency that the triboelement will generate during the run-in process are determined. Calculations of the informative frequency must be performed for the triboelement material on which the piezo element will be installed.
4. Taking into account the noise coming from the equipment, the cluster *K1* in the frame is determined, as well as the sufficiency of the length of the frame being registered. The sufficiency of the frame length is established using the value of the autocorrelation coefficient, the calculation method of which is presented in [14].
5. According to the formulas presented in [14], the values of the informative amplitudes of the *K4* cluster are determined.
6. According to the formulas given in [14], the values of the peak factors of the AE signal from the friction zone of tribosystems are determined and a relationship is established with the numerical values of the rate of wear during running-in - the peak factor of the *K4* cluster.

To perform an experimental verification of the modeling results with experimental data, an experimental setup with a ring-ring contact kinematic scheme was used. The block diagram of the experimental equipment for registration and processing of AE signals from the friction zone is presented in Fig. 1.

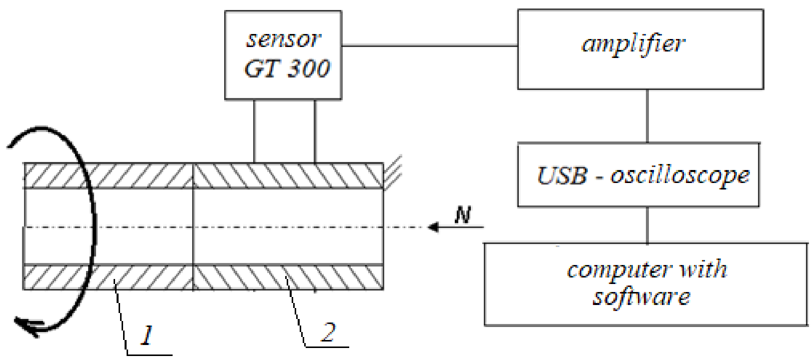


Fig. 1. Block diagram of the experimental equipment for registration and processing of AE signals: 1 - moving triboelement; 2 - fixed triboelement; N - load

The AE signal from the friction zone is registered by a broadband sensor GT300 (100 - 800 kHz), fig. 1, which was installed on a stationary triboelement, was transmitted to the amplifier, then, in analog form, to the PV6501 USB oscilloscope, which performs the functions of an analog-to-digital converter and a spectrum frequency analyzer at the same time. After processing in the USB oscilloscope, the signal in digital code enters the computer, where it is processed by special software.

The lower bandwidth of the signal is 50 kHz, which does not allow recording signals from test equipment (friction machines). The upper bandwidth of the signal is 1,5 MHz.

USB oscilloscope bandwidth, fig. 1, is 20 MHz, which is many times higher than the selected working bandwidth of the signal. Thus, with the help of low- and high-frequency filters, the AE signal from the friction zone in the band 50 - 1500 kHz was recorded and analyzed in the conducted studies.

The USB oscilloscope works in standby mode and is started on command for the registration time, the registration time is 1×10^{-3} s. This time was chosen based on the analysis of the AE signal at a steady state using the autocorrelation function [14].

When checking the homogeneity of variances of selected frames of AE signals in the tribosystem run-in mode, as well as the reproducibility of results from frame to frame, the ISO 5725 standard recommends using the Cochran criterion. The Cochran criterion allows you to compare the homogeneity of dispersions of the results of the analysis of AE signals from different frames. The degree of variability of the results of measurements of AE signals for different designs of tribosystems and their operating conditions was estimated using the coefficient of variation [14].

The root-mean-square absolute deviation for the volumetric wear rate and friction coefficient was calculated according to the formulas given in the ISO 5725 standard. The experimental sample arrays for volumetric wear rate and friction coefficient were checked for compliance with the normal distribution law. The results of experimental studies according to the investigated factors and levels of variation were checked for homogeneity and reproducibility from experiment to experiment according to the Cochrane criterion.

Adequacy of theoretical values obtained by expressions (1) and (2) with experimental data was checked using Fisher's *F*-test. For this purpose, adequacy variances and reproducibility variances were calculated.

In fig. 2 and fig. 3 shows the theoretical and experimental dependences of tribosystem run-in (the value of the change in volumetric wear rate and friction coefficient) over time when the shape coefficient K_f of the tribosystem changes. The shape coefficient of the tribosystem was changed due to the friction area F_{fr} stationary triboelement. Tribosystem "steel 40X+Br.AZH 9-4", lubricating medium - engine oil M-10G2к (E_u= 3,6·10^{14}J/m^3). Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. The tests were carried out on three designs of "ring-ring" tribosystems, where the area of the fixed, bronze triboelement was: F_{fr}= 0,00006 m^2, (K_f=5 m^{-1}); F_{fr}= 0,00015 m^2, (K_f=12,5 m^{-1}); F_{fr}= 0,00024 m^2, (K_f=20 m^{-1}). The area of the movable triboelement, steel 40X, in all three designs was F_{max} =0,0003 m^2. Load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

The results of the obtained array of experimental values allow us to draw a conclusion about the significant influence of the shape factor of the tribosystem on the nature of running-in. A small value of the shape factor of the tribosystem shortens the running-in time, but increases the volumetric rate of wear and the coefficient of friction. Conversely, an increase in the shape factor of the tribosystem makes the running-in process take longer, but the values of the volumetric wear rate and the friction coefficient decrease.

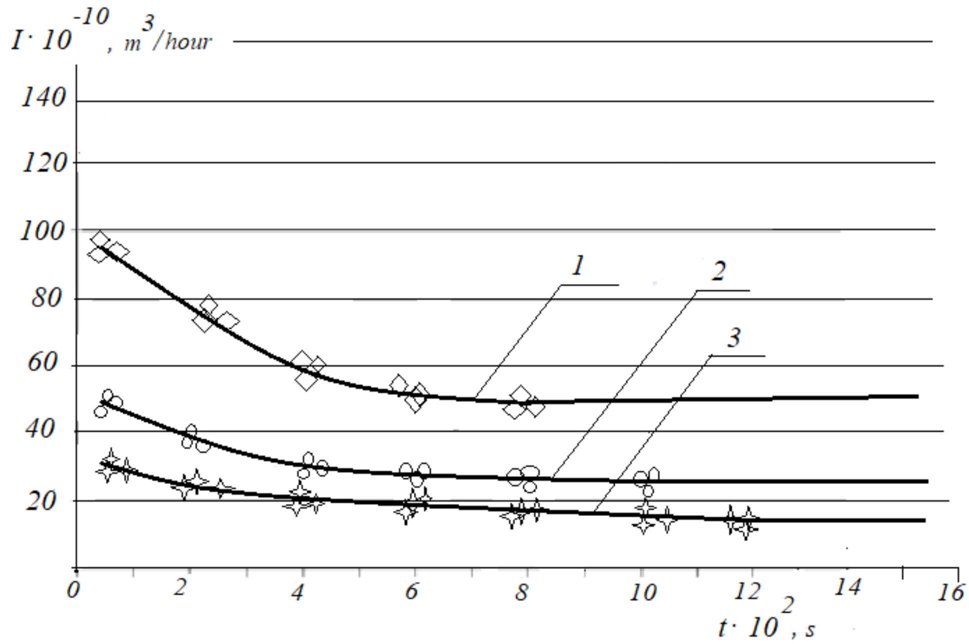


Fig. 2. Dependences of changes in the volume rate of wear during the running-in of tribosystems with different shape factors K_f: 1 – K_f=5 m^{-1}; 2 – K_f=12,5 m^{-1}; 3 – K_f=20 m^{-1}

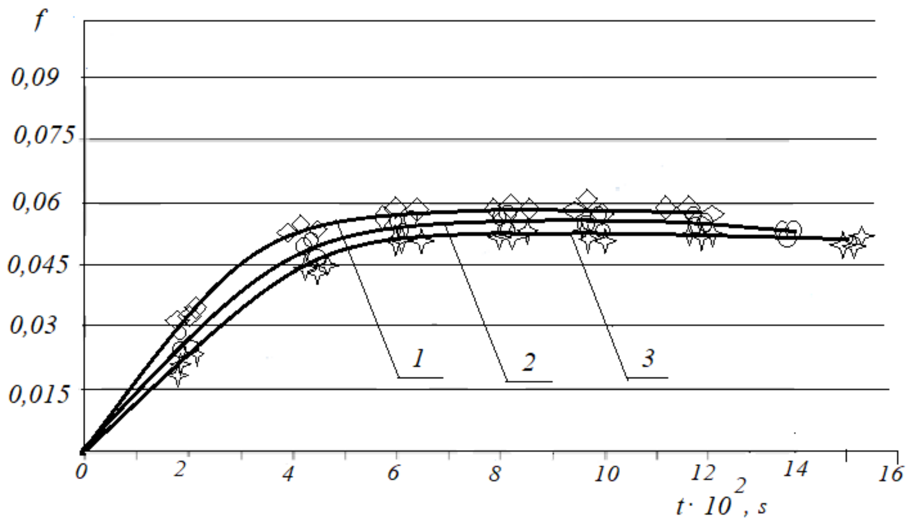


Fig. 3. Dependencies of the change in the friction coefficient during the running-in of tribosystems with different form factors K_f: 1 – K_f=5 m^{-1}; 2 – K_f=12,5 m^{-1}; 3 – K_f=20 m^{-1}

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The calculation of the coefficient of variation and the modeling error of the tribosystem running-in process when the shape factor changes from the minimum value to the maximum, for the given conditions of the experiment, shows that the coefficient of variation is v = 15,7%, and the modeling error does not exceed e = 7,7%,

The second constructive factor characterizing the tribosystem is the tribological properties of the lubricating medium, E_u. In fig. 4 and fig. 5 shows the theoretical and experimental dependences of lubrication of tribosystems over time with different lubricating media: hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); motor oil M–10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3); transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3).

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. Kinematic scheme of the "ring-ring" tribosystem, shape factor of the tribosystem K_f = 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The presented results of experimental studies confirm the results of modeling and allow us to draw a conclusion about the significant influence of the tribological properties of the lubricating medium on the running-in time and the volume rate of wear and the coefficient of friction. The coefficient of variation is constant and is at the level v = 12,3%, the modeling error does not exceed e = 8,9%,

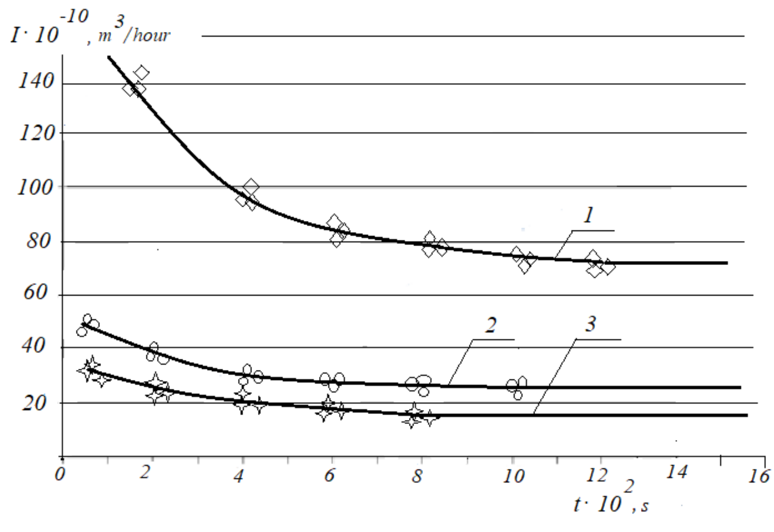


Fig. 4. Dependencies of changes in the volumetric rate of wear during the running-in of tribosystems with different lubricating media E_u: 1 - hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); 2 - motor oil M – 10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3); 3 - transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3)

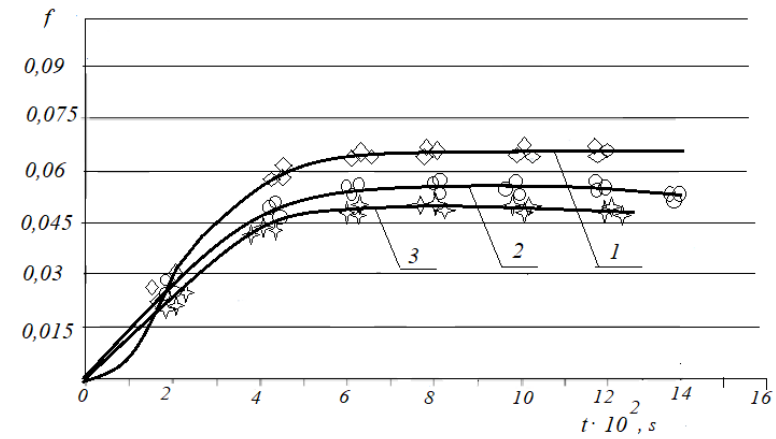


Fig. 5. Dependencies of the change in the friction coefficient during the run-in of tribosystems with different lubricating media E_u: 1 - hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); 2 - motor oil M – 10G2к (E_u= 3,6·10^{14} J/m^3); 3 - transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3)

The third constructive factor that characterizes the tribosystem is the combination of materials of moving and stationary triboelements. In fig. 6 and fig. 7 presents the theoretical and experimental values of the change in the running-in time (the value of the change in the volumetric rate of wear and the coefficient of friction) for different combinations of materials in the tribosystem. The following designs of tribosystems were tested: steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); steel 40X + Br.AZH 9-4, (RS_{TS}=332,5 m^{-1}). For all designs, the moving triboelement was made of steel 40X (HRC 52-54).

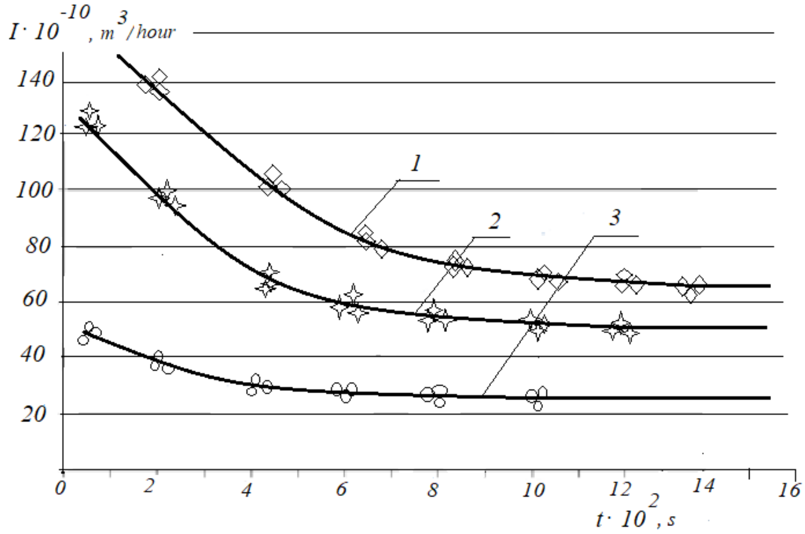


Fig. 6. Dependencies of the change in the volumetric rate of wear during the running-in of tribosystems with different composite materials RS_{TS}: 1 – steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); 2 - steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); 3 - steel 40X + Br.AZH 9-4, (RS_{TC}=332,5 m^{-1})

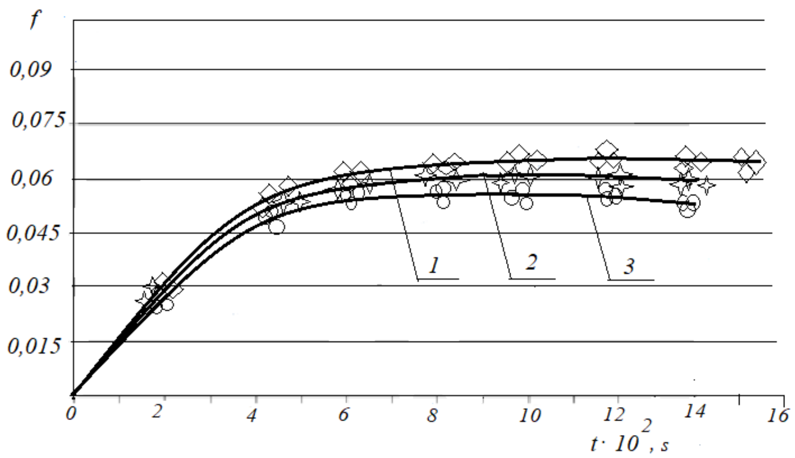


Fig. 7. Dependencies of the change in the friction coefficient during the running-in of tribosystems with different combined materials RS_{TS}: 1 – steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); 2 - steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); 3 - steel 40X + Br.AZH 9-4, (RS_{TS}=332,5 m^{-1})

Conditions of the experiment. The lubricating medium is motor oil M-10G2к. (E_u= 3,6·10^{14}J/m^3). Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f= 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The results of the obtained array of experimental values allow us to draw a conclusion about the significant influence of composite materials in the tribosystem on the dependence of tribosystem run-in. Little value of rheological properties of combined materials and tribosystem RS_{TS} increases break-in time and increases volumetric wear rate and friction coefficient. Conversely, an increase in size RS_{TS} reduces the running-in time and reduces the values of the volumetric rate of wear and the coefficient of friction.

Calculation of the coefficient of variation and the modeling error of the tribosystem running-in process when the rheological properties of the combined materials in the tribosystem change RS_{TS}, shows that the coefficient of variation is v = 18,4%, and the modeling error does not exceed e = 10,3%.

Technological factors that affect the change of running-in dependencies are represented by the parameters of the roughness of the friction surfaces (Ra, Sm) moving and fixed triboelements. In fig. 8 and fig. 9 presents the theoretical and experimental values of the change in the volumetric rate of wear and the friction coefficient during the run-in of tribosystems with different values of the roughness of the friction surfaces (Ra, Sm).

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f= 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s. Roughness of friction surfaces: Ra = 0,16 micron; Ra = 0,2 micron; Ra = 0,24 micron. Average pitch of inequalities: Sm=0,4 mm.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

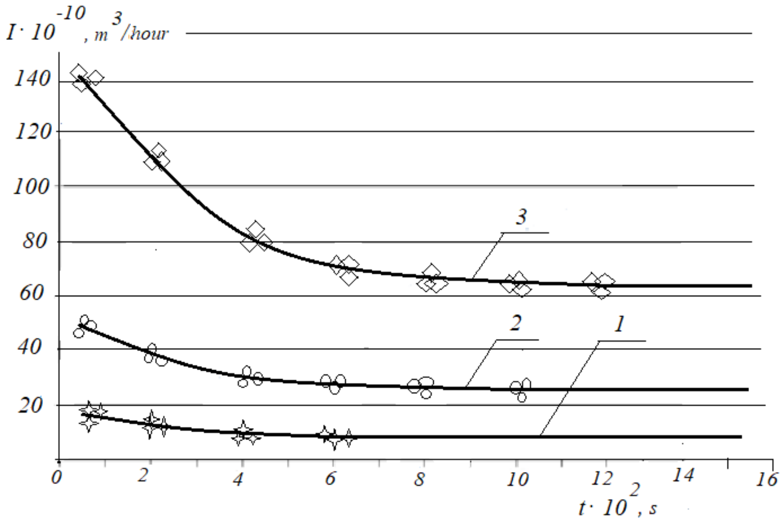


Fig. 8. Dependencies of the change in the volumetric rate of wear during the run-in of tribosystems for different values of the roughness of the friction surfaces *Ra*: 1 – *Ra* = 0,16 micron; 2 – *Ra* = 0,2 micron; 3 – *Ra* = 0,24 micron

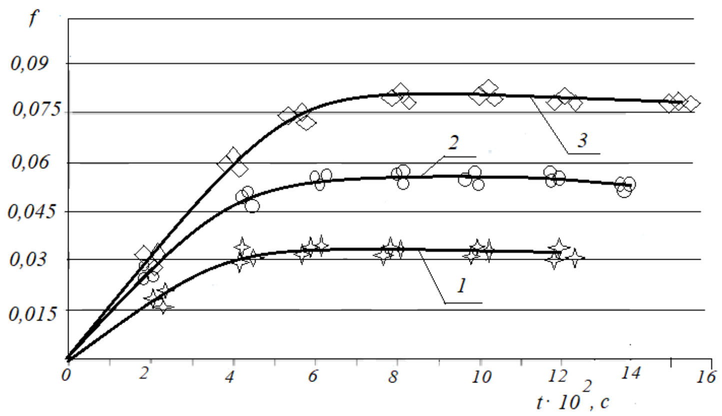


Fig. 9. Dependencies of the change in the friction coefficient during the running-in of tribosystems for different roughness values on the friction surfaces *Ra*: 1 – *Ra* = 0,16 micron; 2 – *Ra* = 0,2 micron; 3 – *Ra* = 0,24 micron

The results of experimental studies confirm the results of modeling and allow us to draw a conclusion about the significant influence of the roughness of the friction surfaces on the character of the tribosystems' running-in. When changing the value Ra = 0,16 micron to the size Ra = 0,24 micron, the coefficient of variation increases from the value v = 4,5% to the size v = 26,5%. The value of the modeling error in the entire range of studies is e = 12,5%. Operating factors that affect the nature of tribosystems running-in are expressed through parameters: load and sliding speed.

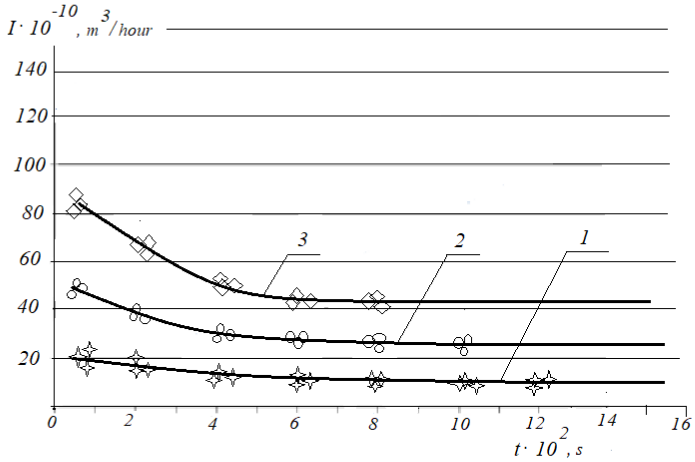


Fig. 10. Dependencies of the change in the volumetric rate of wear during tribosystem running-in for different load values *N*: 1 – *N* = 750 N; 2 - *N* = 1500 N; 3 - *N* = 2250 N

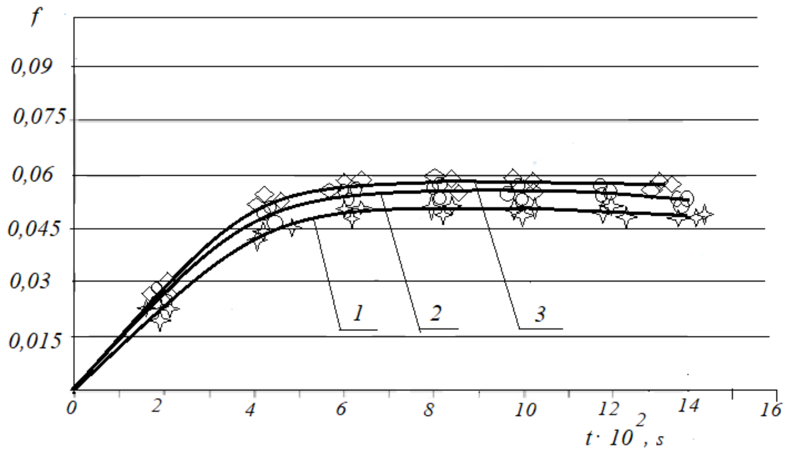


Fig. 11. Dependencies of the change in the friction coefficient during the tribosystem running-in for different load values *N*: 1 – *N* = 750 N; 2 - *N* = 1500 N; 3 - *N* = 2250 N

In fig. 10 and fig. 11 presents the theoretical and experimental values of the change in the character of the tribosystem run-in when the load *N* changes, and fig. 12 and fig. 13 when changing the sliding speed v_{sl}.

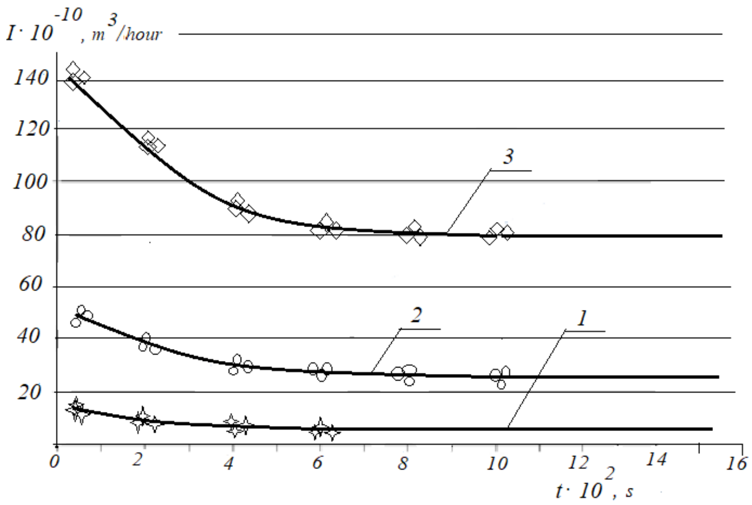


Fig. 12. Dependencies of the change in the volumetric rate of wear during tribosystem running-in for different values of the sliding speed v_{sl}: 1 – v_{sl} = 0,2 m/s; 2 – v_{sl} = 0,5 m/s; 3 – v_{sl} = 0,8 m/s

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f = 12,5 m^{-1}. Lubricating medium - motor oil M – 10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3).

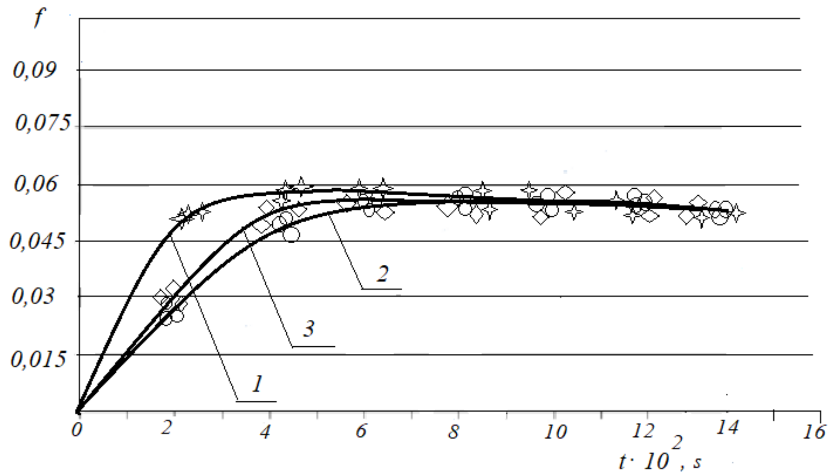


Fig. 13. Dependencies of the change in the friction coefficient during tribosystem running-in for different sliding speed values v_{sl} : 1 – v_{sl} = 0,2 m/s; 2 – v_{sl} = 0,5 m/s; 3 – v_{sl} = 0,8 m/s

Roughness of friction surfaces: Ra = 0,2 micron; average step of inequalities: Sm = 0,4 mm. Load N = 750; 1500; 2250 N; sliding speed v_{sl} = 0,2; 0,5; 0,8 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The results of experimental studies confirm the significant influence of load and sliding speed on the nature of tribosystems' running-in. An increase in the amount of load contributes to a decrease in the running-in time, which is positive, but it increases the volume rate of wear, fig. 10, and the coefficient of friction, fig. 11. The coefficient of variation of the values of the volumetric wear rate and the coefficient of friction increases from the value v = 6,4% to the size v = 20,8%. The value of the modeling error in the entire range of studies is e = 11,7%.

When changing the value of the sliding speed, it was established that the minimum run-in time is characteristic for the minimum sliding speed. At the same time, the volumetric rate of wear has minimal values, fig. 12, and the friction coefficient, maximum values, fig. 13. The coefficient of variation is within the limits v = 13,5 - 18,6%. The value of the modeling error in the entire range of studies is e = 12,9%.

Based on the results of theoretical and experimental data, it is possible to build a ranking of factors that have the greatest influence on the running-in process. In the first city - the roughness of the friction surfaces, the coefficient of variation v = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation v = 20,8%. On the third city - the value of the sliding speed during running-in, the coefficient of variation v = 18,6%. The conclusion made must be taken into account when developing a rational program for running in tribosystems in conditions of extreme lubrication.

Conclusions

An experimental verification of the mathematical model of tribosystem running-in processes was carried out. Comparing the theoretically obtained results, by modeling according to the developed models, with experimental data, it was established that the mathematical model adequately reflects the running-in processes taking into account the changes in constructive, technological and operational factors. Applying the Cochrane criterion, it was established that the obtained experimental results are homogeneous and reproducible. The maximum value of the coefficient of variation of the values of the volumetric wear rate and the coefficient of friction is within the limits v = 12,3 - 26,5%. The value of the simulation error is within the limits v = 7,7 - 12,9%.

A rating of factors that maximally affect the processes of running-in of tribosystems in the conditions of extreme lubrication has been obtained. In the first place - the roughness of the friction surfaces, the coefficient of variation v = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation v = 20,8%. On the third place - the value of the sliding speed during running-in, the coefficient of variation v = 18,6%. The conclusion made must be taken into account when developing a rational program for running in tribosystems in conditions of extreme lubrication.

References

1. Khonsari, M. M., Ghatrehsamani, S., & Akbarzadeh, S. On the running-in nature of metallic tribo-components: A review. *Wear*, 2021, *474*, 203871. https://doi.org/10.1016/j.wear.2021.203871 [English]

2. Sun, G. Frictional Running-In Status Identification for Ring-on-Disc Tribosystem by the Visualization of Friction-Induced Attractors. *Available at SSRN, 2022, 4291551*. https://dx.doi.org/10.2139/ssrn.4291551 [English]

3. Zhou, Y., Wang, Z., & Zuo, X. Multi-objective optimization of three-stage running-in process for main bearing of marine diesel engine. *Journal of Tribology*, 2023, 1-18. https://doi.org/10.1115/1.4062298 [English]

4. Maier, M., Pusterhofer, M., & Grün, F. Wear simulation in lubricated contacts considering wear-dependent surface topography changes. *Materials Today: Proceedings*, 2023, https://doi.org/10.1016/j.matpr.2023.01.424 [English]

5. Johansson, P., Marklund, P., Björling, M., & Shi, Y. Effect of roughness on the running-in behavior and tribofilm formation of carbon fiber reinforced PTFE composite in trace moisture environment. *Wear*, 2022, *500*, 204367. https://doi.org/10.1016/j.wear.2022.204367 [English]

6. Hsia, F. C., Elam, F. M., Bonn, D., Weber, B., & Franklin, S. E. Tracing single asperity wear in relation to macroscale friction during running-in. *Tribology International*, 2021, *162*, 107108. https://doi.org/10.1016/j.triboint.2021.107108[English]

7. Ghatrehsamani, S., Akbarzadeh, S., & Khonsari, M. M. Experimental and numerical study of the running-in wear coefficient during dry sliding contact. *Surface Topography: Metrology and Properties*, 2021, *9*(1), 015009. DOI 10.1088/2051-672X/abbd7a [English]

8. Vojtov V. A., Biekirov A. Sh., Voitov A. V., Tsymbal B. M. Running-in procedures and performance tests for tribosystems // *Journal of Friction and Wear*, 2019, Vol. 40, No. 5, pp. 376–383. DOI: 10.3103/S1068366619050192 [English]

9. Voitov, A. Mathematical model of running-in of tribosystems under conditions of boundary lubrication. Part 1. Development of a mathematical model**.** *Problems of Tribology***,** 2023, V. *28*, No 1/107, P. 25-33. https://doi.org/10.31891/2079-1372-2022-107-1-25-33 [English]

10. Voitov, A. Structural identification of the mathematical model of the functioning of tribosystems under conditions of boundary lubrication. *Problems of Tribology*, 2021, V. 26, No 2/100, P. 26-33. https://doi.org/10.31891/2079-1372-2021-100-2-26-33 [English]

11. Vojtov V.A., Voitov A.V. Assessment of the quality factor of tribosystems and relationship with tribological characteristics. *Problems of Tribology*, 2020, V. 25, No 4/98, P. 20-26. https://doi.org/10.31891/2079-1372-2020-98-4-20-26 [English]

12. Voitov A. V. Development of a mathematical model of stationary processes in tribosystems under boundary lubrication conditions. Technical service of agro-industrial, forestry and transport complexes. – Kharkiv: KhNTUSG, - 2019. – Iss. 16, p. 16-28. [Russian]

13. Voitov V., Voitov A. Modeling the limits of operation of tribosystems under conditions of boundary lubrication // Problems of Friction and Wear. - 2021, - no. 4 (93). - P. 58-69. https://doi.org/10.18372/0370-2197.4(93).16262 [Ukr]

14. Victor Vojtov, Katherine Fenenko, Anton Voitov, Andriy Hrynkiv, Oleg Lyashuk, Yuriy Vovk. Methodical Approach to Using Acoustic Emission Method for Tribosystem Monitoring**.** *Tribology in Industry*, 2022, Vol. 44, No. 3, pp. 470-481. https://doi.org/10.24874/ti.1298.05.22.08 [English]

Войтов А.В. Математична модель припрацювання трибосистем в умовах граничного мащення. Частина 2. Результати моделювання

В роботі наведено результати математичного моделювання процесів припрацювання трибосистем при зміні різних факторів: конструктивних параметрів трибосистем, які враховуються коефіцієнтом форми; трибологичних властивостей змащувального середовища; реологічних властивостей сполучених матеріалів в трибосистемі; шорсткість поверхонь тертя; навантаження та швидкість ковзання. Порівнюючи теоретично отримані результати, шляхом моделювання за розробленими моделями, з експериментальними даними, встановлено, що математична модель адекватно відображає процеси припрацювання з урахуванням зміни конструктивних, технологічних та експлуатаційних факторів. Застосовуючи критерій Кохрена встановлено, що отримані експериментальні результати однорідні і відтворювані. Максимальне значення коефіцієнта варіації значень об'ємної швидкості зношування та коефіцієнта тертя знаходиться в межах v = 12,3 - 26,5%. Значення похибки моделювання знаходиться в межах v = 7,7 - 12,9%.

Отримано рейтинг факторів, які максимально впливають на процеси припрацювання трибосистем в умовах граничного мащення. На першому місті – шорсткість поверхонь тертя, коефіцієнт варіації v = 26,5%. На другому місті – навантаження на трибосистему під час припрацювання, коефіцієнт варіації v = 20,8%. На третьому місті – величина швидкості ковзання під час припрацювання, коефіцієнт варіації v = 18,6%. Зроблений висновок необхідно враховувати при розробці раціональної програми припрацювання трибосистем в умовах граничного мащення.

Представлено методичний підхід застосування метода акустичної емісії при дослідженні процесів припрацювання трибосистем. В роботі доведено, що для визначення об`ємної швидкості зношування під час припрацювання трибосистем, необхідно реєструвати та аналізувати четвертий кластер з загального сигналу акустичної емісії. Джерелами генерації сигналу четвертого кластеру є мікрорізання і пластична деформація виступів шорсткості поверхні тертя, яке характерне для перших етапів припрацювання.

Keywords: трибосистема; припрацювання; математична модель припрацювання; граничне мащення; коефіцієнт форми; трибологічні властивості змащувального середовища; реологічні властивості сполучених матеріалів; швидкість зношування; коефіцієнт тертя

Problems of Tribology, V. 28, No 2/108-2023, 56-61

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-56-61

Dependence of the wear rate on the microhardness of the coating of the auger hehydration in a garbage truck for municipal solid waste

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

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

Received: 07 May 2023: Revised 31 May 2023: Accept 10 June 2023

Abstract

The article is dedicated to the study of the influence of the microhardness of the auger coating on its wear resistance during the dehydration of municipal solid waste in a garbage truck. The use of mathematical tools and appropriate regression analysis software allowed to determine the dependence between the auger wear rate and the microhardness of the coating. A graphical representation of the change in auger wear rate based on the microhardness of the coating was made up, confirming a significant convergence with the obtained dependence. The graphs illustrating the impact of the microhardness of the screw coating on its wear rate demonstrate the feasibility of increasing it. It was found that after operating and wearing out over a distance of s = 56850 m during the dehydrating of solid municipal waste in a garbage truck, increasing the microhardness of the coating from 2.7 GPa to 33.2 GPa leads to a decrease in energy consumption by 19 kWh/tons or 12% and reduces the cost of the dehydrating process. The feasibility of conducting additional research to determine further ways to increase the wear resistance of the auger was established.

Key words: wear, wear resistance, wear rates, coating microhardness, auger press, garbage truck, dehydration, municipal solid waste, regression analysis.

Introduction

One of the important tasks of municipal engineering is to improve the wear resistance and reliability of the executive components of machines [1, 2]. One of the promising technologies for primary processing of municipal solid waste (MSW), aimed at reducing the costs of MSW transportation and its negative impact on the environment, is their dehydration during the loading process into garbage trucks, accompanied by associated processes of pre-compaction and partial shredding. The dehydration of MSW in the garbage truck is performed by a tapered auger, the surfaces of which undergo intensive wear due to the presence of waste components with abrasive properties, such as small metal objects, glass, stones, ceramics, polymer materials, and bones. The aggressive corrosive environment is formed by the moisture present in the MSW in the range of 39...92% by weight. Augers are typically made from iron-based alloys. The application of wear-resistant coatings to increase wear resistance [3, 4] is substantiated. Therefore, determining the dependence of wear rate on the microhardness of the coating on the dehydrating auger in the garbage truck for municipal solid waste is a current task.

Analysis of recent research and publications

The evaluation of the effectiveness of the application of nano-sized coatings on surfaces subject to abrasive and erosive wear during operation of compressor blades of gas turbine engines, augers of mechanical mills, etc. is carried out in the article [3]. Two types of nanostructured coatings were chosen for the study – multilayer nanocoatings based on titanium and zirconium nitrides (Ti/Zr) and composite chromium coating with diamond nanoparticles (Cr-UDD). According to the results of gravimetric measurements, it was established that the rate of wear of the Ti/Zr nanolayer coating is 2 and 3.3 times lower than that of monolayer Ti and Zr, respectively.

The work [1] examines the peculiarities of the influence of prior laser treatment on the phase composition, structure, and properties of nitrogenized layers on steels. It is shown that the qualitative and quantitative changes in the nitrogenized layer are determined by the pre-formed structural and phase state. The main dependencies of the influence of contour-radiation schemes of laser strengthening on the tribological characteristics of coatings are established.

In the materials of the work [5], the physical justifications for a significant increase in the strength of nano-layered metal composite materials compared to the additive strength of components are given. From a unified perspective, the main technological methods of forming multilayer nanostructures in alloys are considered. It is experimentally shown that the use of nano-layered steel and copper composites allows for a significant increase in wire strength and approach the lower limit of the theoretical value for iron alloys.

The construction of a mathematical model for calculating the wear rate of tribological elements in a tribological systems under conditions of corrosion-abrasive wear is published in [6]. The input parameters included active acidity, abrasiveness, roughness, load, and sliding speed. The theoretical study established the degree of influence of these factors on the wear rate: abrasiveness being the most significant factor, followed by the level of active acidity and load, respectively, in decreasing order of impact.

To reduce the degree of damage to granular material during its transportation, a new design of an auger with a sectional elastic surface is proposed [7]. In order to determine the influence of structural, kinematic, and technological parameters of the elastic auger on the time and path of free movement of particulate material between sections, as well as to eliminate the possibility of interaction between the granular material and the non-working surface of the auger working element to reduce its damage, a dynamic model was developed. This model was used to perform a theoretical calculation of the interaction between the grain and the elastic section of the auger.

The work [8] is dedicated to determining the regularities of microstructure formation in Cr-Ni-Fe-C alloys during the surfacing with powder ribbons PL AN-101 and PL AN-111. The aim is to determine the optimal microstructural state, alloying level, and increase the durability of coatings under high-temperature wear conditions. Recommendations are provided regarding the application areas of wear-resistant coatings deposited with the mentioned powder ribbons. It is established that in order to prevent the formation of graphite in the structure of the surfacing and considering the possible local increase in carbon content up to 5.5%, the nickel concentration should not exceed 13...14%.

In the materials of article [9], the influence of geometric parameters on the productivity and design of a briquetting machine is investigated using a pressure model based on the theory of piston flow. An analytical model using the pressure model was also developed based on the Archard wear law to study the wear of biomass briquetting machine augers. This model satisfactorily predicted the wear of the auger and showed that the rotational speed and material selection have the greatest impact on wear. It was found that the wear volume exponentially increases towards the end of the auger, where the pressure is highest. It is determined that modifying the auger design to select optimal geometry and speed, along with the appropriate material selection, can increase the productivity of the biomass briquetting machine and extend the service life of the auger.

As a result of morphological investigations [10] of friction surfaces, it was determined that the improvement of tribological properties is associated with the formation of a discrete anti-friction coating on the steel surface during frictional interaction with developed polymer composite materials. The increase in microhardness of the steel surface at filler concentrations in polymer composite materials from 0 to 10% is explained by the formation of an anti-friction coating, which is most stable at a filler content of 10%. Further decrease in microhardness with increasing filler content from 10 to 30% is related to its abrasive action on the friction pair, which partially destroys the obtained stable anti-friction coating.

The wear of a twin-auger extruder for rigid PVC resins was studied in the materials of article [11] using numerical flow modeling with power-law viscosity functions of the resins. The pressures around the cylinder during the extrusion of two rigid PVC resins in a laboratory extruder with a diameter of 55 mm and the forces acting on the auger core were determined.

The work [12] investigated the peculiarities of wood chip pressing in auger machines, as well as the processes occurring at different sections of the auger. Formulas were derived that allow for the calculation of loads acting on the auger flights and the determination of pressing power. Specific energy consumption and the degree of heating of the raw material during pressing were determined.

Using Box-Wilson rotatable central composite design, experimental results of the dehydration process of MSW were obtained and published in the work [13]. Quadratic regression equations with first-order interaction effects were obtained for the following response variables: moisture content and density of pre-compacted and dehydrated MSW, maximum power of the drive motor, energy consumption of MSW dehydration. This allowed for determining the optimal equipment parameters for dehydration based on the criterion of minimizing energy consumption, including the auger rotation frequency, the ratio of radial clearance between the auger and the housing, and the ratio of the core diameter of the auger to the outer diameter of the auger on the last turn, for both mixed and "wet" MSW.

An improved mathematical model of the operation of the municipal solid waste dehydration drive in the garbage truck taking into account the wear of the auger is proposed [14], which made it possible to determine by means of a numerical study of the dynamics of this drive during start-up that as the wear of the auger increases, the pressure of the working fluid at the input of the hydraulic motor of the drive increases, and the angular velocity and the rotation frequency of the auger is significantly reduced with constant supply of the working fluid. Power-laws of changes in the nominal values of pressures at the hydraulic motor inlet, angular velocity and rotation frequency of the auger depending on the amount of its wear were determined, the last of which describes the deviation from the optimal rotation frequency of the auger during its wear and was used to determine the energy intensity of solid waste dehydration taking into account the wear of the auger. It was established that the wear of the auger by 1000 μm leads to an increase in the energy consumption of solid waste dehydration by 11.6%, and, therefore, to an increase in the cost of their dehydration in the garbage truck and an acceleration of the wear process.

In the materials of the work [15], logarithmic dependencies of auger wear are determined depending on the hardness of its surface for different values of the friction path. Conducting an additional regression analysis made it possible to obtain the regularity of auger wear depending on the hardness of its surface and friction path, by means of which it was established that during two-week operation and wear of the auger during the dehydration of solid municipal waste in the garbage truck, the hardness of the auger surface increased from 2.31 GPa to 10.05 GPa leads to a decrease in the rate of growth of the energy intensity of dehydration of solid municipal waste from 16.7% to 1.5%, and, therefore, to a decrease in the cost of the process of their dehydration in the garbage truck.

Aims of the article

Determining the dependence of the wear rate on the microhardness of the coating of the auger dehydration in a garbage truck for solid municipal waste.

Methods

Determining the paired regularity of the rate of wear from the microhardness of the coating of the dehydrating auger in the garbage truck of municipal solid waste was carried out by the method of regression analysis. Regression was determined on the basis of linearization transformations, which allow to reduce the non-linear dependence to a linear one. The coefficients of the regression equation were determined by the method of least squares using the developed computer program "RegAnalyz", which is protected by a certificate of copyright registration for the work.

To determine the energy intensity of solid waste dehydration, taking into account the wear of the auger, the following laws were used [14]:

$$\begin{aligned} E = {} & 1504 - 15,92w_0 + 0,3214\rho_0 - 1,069n(u) - 2061(\Delta_{aug} + u)/(D_{\min} - 2u) - 1947(d_{\min} - \\ & -2u)/(D_{\min} - 2u) + 9,118\cdot 10^{-4} w_0\rho_0 + 0,002142w_0 n(u) + 18,12w_0(\Delta_{ш} + u)/(D_{\min} - 2u) - \\ & -2,115w_0(d_{\min} - 2u)/(D_{\min} - 2u) + 4,392\cdot 10^{-4}\rho_0 n(u) - 2,005\rho_0(\Delta_{aug} + u)/(D_{\min} - 2u) + \\ & +0,3361\,\rho_0(d_{\min} - 2u)/(D_{\min} - 2u) + 0,09031w_0^2 - 7,923\cdot 10^{-4}\rho_0^2 + 0,008241n(u)^2 + \\ & +104172\,[(\Delta_{aug} + u)/(D_{\min} - 2u)]^2 + 1318\,[(d_{\min} - 2u)/(D_{\min} - 2u)]^2\ [\mathrm{kW}\cdot h/\mathrm{tons}]; \end{aligned} \quad (1)$$

$$n = 52,43 - 1,276\cdot 10^{-3}u^{1,5}\ \text{[rpm]}, \quad (2)$$

where E is the energy intensity of solid waste dehydration, kWh/tons;
ρ_0 – initial municipal solid waste density, kg/m^3;
w_0 – initial relative humidity of solid waste, %;
n – nominal auger rotation frequency, rpm;
u – auger wear, m;
Δ_{aug} – radial clearance between the auger and the housing, m;
D_{min} is the outer diameter of the auger on the last turn, m;
d_{min} – the diameter of the auger core on the last turn, m.

Results

The values of the wear rate for coatings with different microhardness are given in the Table 1 [3].

As a result of the regression analysis of the data in the Table 1, the regularity of the change in the rate of wear of the auger depending on the microhardness of the coating is determined:

$$\gamma = \frac{1}{0,1158 + 0,2316\,H}\ \text{[mg/h]}, \quad (3)$$

where γ – wear rate, mg/h; H – coating microhardness, Gpa.

Table 1

Effect of coating microhardness on wear rate [3]

Coating	12X18H10T	Cr	Cr-UDD	ZrN	TiN	TiN/ZrN
Coating microhardness H, GPa	2,7	7,6	10,3	15,2	21,6	33,2
Wear rate γ, mg/hour	0,8941	0,7176	0,2824	0,4	0,2039	0,1216

In the Fig. 1 is shown the graphical dependence of the change in the rate of wear of the auger on the microhardness of the coating, constructed using dependence (3), which confirms the sufficient convergence of the obtained regularity compared to the data given in Table 1.

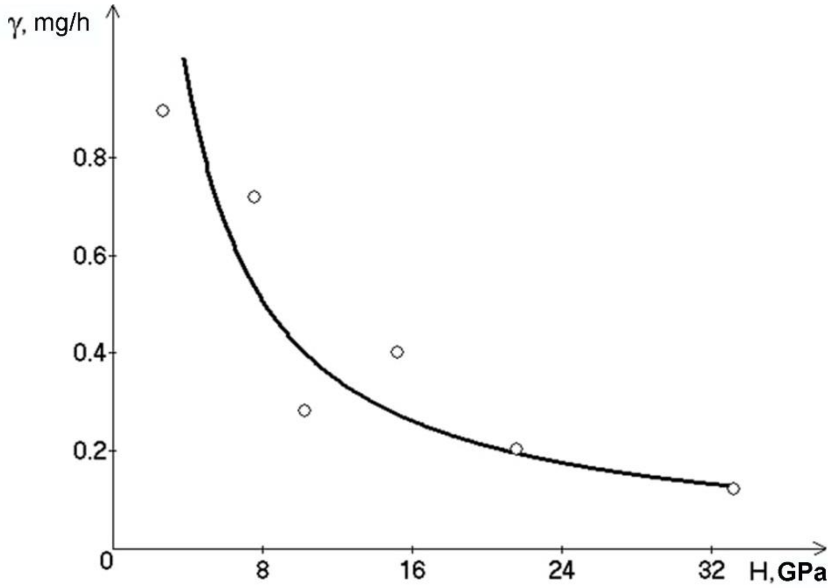


Fig. 1. Dependence of the change in the auger wear rate depending on the microhardness of the coating: actual ○, theoretical —

The results of the regression analysis are shown in Table 2, where cells with the maximum values of the correlation coefficient R for paired regression are marked in gray.

Table 2

The results of the regression analysis of the dependence of the change in the wear rate of the auger on the microhardness of the coating

N	Type of regression	Correlation coefficient R	N	Type of regression	Correlation coefficient R
1	$y = a + bx$	0.84993	9	$y = ax^b$	0.91600
2	$y = 1 / (a + bx)$	0.95706	10	$y = a + b \cdot \lg x$	0.93091
3	$y = a + b / x$	0.87496	11	$y = a + b \cdot \ln x$	0.93091
4	$y = x / (a + bx)$	0.95129	12	$y = a / (b + x)$	0.95705
5	$y = ab^x$	0.92861	13	$y = ax / (b + x)$	0.65429
6	$y = ae^{bx}$	0.92861	14	$y = ae^{b/x}$	0.78573
7	$y = a \cdot 10^{bx}$	0.92861	15	$y = a \cdot 10^{b/x}$	0.78573
8	$y = 1 / (a + be^{-x})$	0.46369	16	$y = a + bx^n$	0.73056

It was established that the wear rate of the auger decreases according to a hyperbolic pattern when the microhardness of the coating increases.

In the Fig. 2 shows the graphical dependence of the effect of the microhardness of the auger coating of the device for dehydrating municipal solid waste on the energy intensity of the process (when it wears out along the path s = 56850 m [15]), constructed using regularities (1-3).

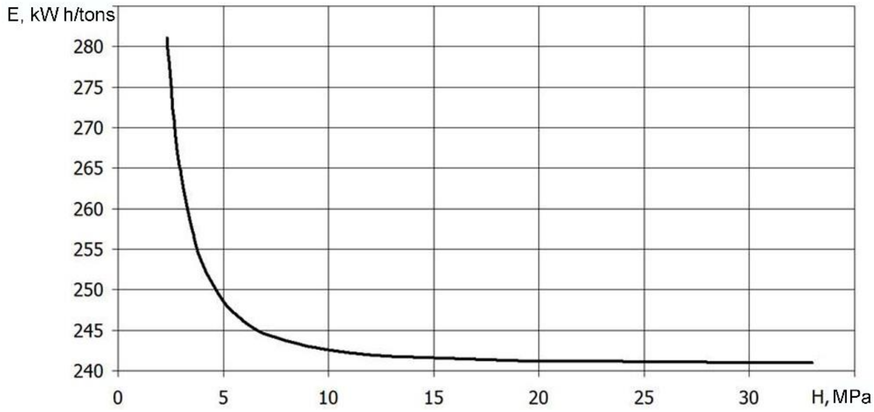


Fig. 2. The influence of the microhardness of the auger coating on the energy intensity of the municipal solid waste dehydration process after its operation and wear on the path *s* = 56850 m

From the Fig. 2 shows that after operation and wear on the path s = 56850 m during municipal solid waste (MSW) dehydration in the garbage truck, the increase in the microhardness of the auger coating from 2.7 GPa to 33.2 GPa leads to a decrease in energy consumption by 19 kWh/t or 12% and to reducing the cost of the solid waste dehydration process in the garbage truck, which indicates the importance of determining further ways to increase its wear resistance.

Conclusions

The hyperbolic dependence of the auger wear rate change depending on the microhardness of the coating was determined. It was established that after operation and wear on the path *s* = 56850 m during the dehydration of municipal solid waste (MSW) in a garbage truck, an increase in the microhardness of the auger coating from 2.7 GPa to 33.2 GPa leads to a decrease in energy consumption by 19 kWh/tons or 12% and to a decrease in price of the process of municipal solid waste dehydration in the garbage truck. Therefore, the determination of further ways of increasing the wear resistance of the auger require additional research.

References

1. Kindrachuk M. V., Yahya M. S., Kornienko A. O., Kindrachuk V. M., Ischuk N. V. (2008) Vyznachennia parametriv dyskretnoi struktury pokryttiv trybotekhnichnoho pryznachennia [Determination of the parameters of the discrete structure of coatings for tribotechnical purposes]. Problems of friction and wear, 50, 5-15.

2. Dykha O.V.(2018) Rozrahunkovo-eksperymental'ni metody keruvannja procesamy granychnogo zmashhuvannja tehnichnyh trybosystem [Computational and experimental methods of controlling processes of boundary lubrication of technical tribosystems]: monograph. Khmelnytskyi: KhNU.

3. Sevidova E.K., Gutsalenko Yu.G., Kryukova N.V. (2016). Issledovanie iznosostoykoy effektivnosti kompozitsionnyih TiN/ZrN i Cr-UDD pokryitiy [Investigation of the wear-resistant efficiency of composite TiN/ZrN and Cr-UDD coatings.]. Materials of the 16th int. sci.-tech. Seminar "Modern problems of production and repair in industry and transport", 212-216.

4. Savulyak V.I., Shenfeld V.Y. (2016) Naplavlennia vysokovuhletsevykh znosostiikykh pokryttiv [Deposition of high-carbon wear-resistant coatings], Monograph, Vinnytsia: VNTU.

5. Shpak A.P., Maiboroda V.P., Kunytskyi Yu.A., Revo S.L. (2004) Nanosloistyie kompozitsionnyie materialyi i pokryitiya [Nanolayered Composite Materials and Coatings] . Kyiv: Akademperiodika.

6. Tsymbal B.M. (2017) Naplavlennia vysokovuhletsevykh znosostiikykh pokryttiv [Increasing the wear resistance of screw extruders for the production of fuel briquettes in acidic and alkaline environments]: autoref. thesis ... cand. engineering sciences: 05.02.04 - Friction and wear in machines, Kharkiv, 20.

7. Hevko R.B., Zalutskyi S.Z., Hladyo Y.B., Tkachenko I.G., Lyashuk O.L., Pavlova O.M., ... & Dobizha N.V. (2019). Determination of interaction parameters and grain material flow motion on screw conveyor elastic section surface. INMATEH-Agricultural Engineering, 57(1).

8. Efremenko B.V. (2018). Strukturoutvorennia v naplavlenykh Fe-Cr-Ni-C splavakh, pryznachenykh dlia vykorystannia v umovakh vysokotemperaturnoho znoshuvannia [Structure formation in deposited Fe-Cr-Ni-C alloys intended for use in conditions of high-temperature wear]: thesis ... candidate technical Sciences: 05.02.01 – Materials Science, Zaporizhzhia, 234.

9. Orisaleye J.I., Ojolo S.J., Ajiboye J.S. (2019) Pressure build-up and wear analysis of tapered screw extruder biomass briquetting machines. Agricultural Engineering International: CIGR Journal, 21(1), 122-133.

10. Kabat O.S. (2021) Naukovo-tekhnichni osnovy tekhnolohii vyhotovlennia termostiikykh polimernykh kompozytsiinykh materialiv trybotekhnichnoho pryznachennia [Scientific and technical bases of technology for manufacturing heat-resistant polymer composite materials for tribotechnical purposes]: thesis ... Dr. engineering

Sciences: 05.17.06 - technology of polymer and composite materials, Dnipro, 350.

11. Demirci A., Teke I., Polychronopoulos N. D., Vlachopoulos J. (2021) The Role of Calender Gap in Barrel and Screw Wear in Counterrotating Twin Screw Extruders. Plymers, 13(7), 990.

12. Tataryants M.S., Zavinsky S.I., Troshin A.G. (2015) Razrabotka metodiki raschYota nagruzok na shnek i energozatrat shnekovyih pressov [Development of a method for calculating the loads on the screw and the energy consumption of screw presses] . ScienceRise, 6 (2), 80-84.

13. Bereziuk O.V. (2018) Eksperymentalne doslidzhennia protsesiv znevodnennia tverdykh pobutovykh vidkhodiv shnekovym presom [Experimental study of the processes of dehydration of solid household waste with a screw press]. Вісник Вінницького політехнічного інституту, 5, 18-24.

14. Bereziuk O.V., Savulyak V.I., Kharzhevskyi V.O. (2021) The influence of auger wear on the parameters of the dehydration process of solid waste in the garbage truck. Problems of Tribology, 26(2/100), 79-86.

15. Bereziuk O.V., Savulyak V.I., Kharzhevskyi V.O. (2021) Regression analysis of the influence of augersurface hardness on its wear during dehydration of solid waste in a garbage truck. Problems of Tribology, 26(3/101). 48-55.

Березюк О.В., Савуляк В.І. , Харжевський В.О., Віштак І.В. Залежність швидкості зношування від мікротвердості покриття шнека зневоднення у сміттєвозі твердих побутових відходів

Стаття присвячена дослідженню впливу мікротвердості покриття шнека на його зносостійкість під час зневоднення твердих побутових відходів у сміттєвозі. Використання математичного апарату та відповідних програм регресійного аналізу дозволило визначити закономірність зміни швидкості зношування шнека залежно від мікротвердості покриття. Побудована графічна залежність зміни швидкості зношування шнека залежно від мікротвердості покриття, яка підтвердила достатню збіжність отриманої закономірності. Графіки впливу мікротвердості покриття шнека на швидкість його зношування демонструє доцільність її підвищення. Встановлено, що після експлуатації та зношування на шляху s = 56850 м під час зневоднення ТПВ у сміттєвозі збільшення мікротвердості покриття шнека з 2,7 ГПа до 33,2 ГПа призводить до зниження енергоємності на 19 кВт·год/т або 12% та до здешевлення процесу зневоднення ТПВ у сміттєвозі. Встановлена доцільність проведення додаткових досліджень з визначення подальших шляхів підвищення зносостійкості шнека.

Ключові слова: знос, зносостійкість, швидкості зношування, мікротвердість покриття, шнековий прес, сміттєвоз, зневоднення, тверді побутові відходи, регресійний аналіз.

Problems of Tribology, V. 28, No 2/108-2023, 62-69

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

DOI: https://doi.org/10.31891/2079-1372-2023-108-2-62-69

Review of aspects of processing and use of waste cooking oils as effective lubricants

O. Dykha[1*], M. Hetman[1], A. Staryi[1], T. Kalaczynski[2]

[1]*Khmelnytskyi national University, Ukraine*
[2]*Politechnika Bydgoska im. Jana i Jędrzeja Śniadeckich, Poland*
**E-mail: tribosenator@gmail.com*

Received: 10 May 2023: Revised 10 April 2023: Accept 16 June 2023

Abstract

In connection with environmental pollution and the depletion of oil reserves, biologically based lubricants have received great interest as a replacement for mineral oil-based lubricants. Biolubricants have a number of advantages over mineral lubricants, including high biodegradability, low toxicity, lubricating properties and minimal environmental impact. The presented review describes the main characteristics and properties of biological lubricants, various vegetable oils, which are used as raw materials for the production of biolubricant materials. The physicochemical properties of biological lubricants were analyzed from the point of view of improvement. The technological processes used for the chemical modification of vegetable oils, ensuring the lubricity and anti-wear properties of the obtained biolubricants are determined. Various additives used to improve the properties of biolubricants are also recommended. This review material will provide researchers and practitioners with additional information on the practice of using biolubricants.

Keywords: vegetable oils, food industry waste, environmental friendliness, chemical modification, physical processing, lubrication, wear resistance

Introduction

Worldwide concern over the massive use of petroleum-based products is affecting the production of lubricants in a way that also requires the search for new oil-free technologies. Nowadays, environmental protection requirements [1-6] have turned biodegradability into one of the main parameters from the point of view of choosing base oils and improvers of lubricating properties of materials. It is known that various vegetable oils are suitable as base oils for lubricants. However, the large acreage devoted to industrial oil crops competes with the use of land for food production, and this is a major controversial issue. Thus, the production of biolubricants based on edible vegetable oils has recently been considered an unsustainable practice. In addition,

Main material

Edible vegetable oils are widely used for frying, which is usually carried out at a temperature of 160 to 180 ◦C in the presence of air and moisture. At the same time, chemical changes occur as a result of thermo-oxidative and hydrolytic reactions, isomerization of double bonds, oligomerization and degradation of triglycerides. Thus, the chemical composition of the oil after frying is different from the original fresh oil, it undergoes undesirable physico-chemical changes (among other things, color, smell, viscosity, acidity, general polar compounds). In recent decades, the amount of waste cooking oil (WCO) generated by the food industry, restaurants, fast food establishments and homes has been continuously increasing, at a rate of up to 2% per year, due to the increase in food products and, above all, the consumption of fast food by the population.

There is inadequate disposal of WCO through the sewage system, causing both economic problems and pollution of rivers and soils. On the one hand, the irrational disposal of used cooking oil in the sewer creates problems with the operation and maintenance of municipal sewage treatment plants, which significantly increases the costs of their cleaning.

On the other hand, one liter of waste vegetable oil poured into the environment can pollute 0.5 million liters of water, which will cause serious environmental problems [1-4]. Therefore, proper management of WCO is mandatory to reduce its impact on the global environment and improve their availability for reuse in various industrial processes such as bio-lubricants, biodiesel, asphalt additives and others.

The use of WCO as a feedstock in biodiesel plants is an established practice. However, demand for biodiesel is currently declining to reduce harmful emissions, and many biodiesel plants are closing around the world. Therefore, other methods of reuse should be explored to reduce the negative environmental impact and greenhouse gas emissions of WCO. With this in mind, bio-lubricants can be a way to use waste cooking oil with a dual purpose. First, it can prevent non-food land use; secondly, it can prevent their potential impact if disposed of in the environment. Therefore, other methods of reuse should be explored to reduce the negative environmental impact and greenhouse gas emissions of WCO. With this in mind, bio-lubricants can be a way to use waste cooking oil with a dual purpose. First, it can prevent non-food land use; secondly, it can prevent their potential impact if disposed of in the environment. Therefore, other methods of reuse should be explored to reduce the negative environmental impact and greenhouse gas emissions of WCO. With this in mind, bio-lubricants can be a way to use waste cooking oil with a dual purpose. First, it can prevent non-food land use; secondly, it can prevent their potential impact if disposed of in the environment.

In general, most of the research work related to waste cooking oils focuses on the use of their fatty acid methyl esters for the production of WCO-derived molecules and elucidating their physicochemical characteristics [1-3]. There is insufficient information about the full physicochemical characteristics of the used WCO and the relationship between its physicochemical properties and tribological characteristics.

Therefore, a comparative assessment of waste cooking oil from different food enterprises and an analysis of the influence of their physical and chemical properties on tribological behavior is needed.

This review presents the results of the latest research in the field of using waste cooking oils for the production of technical lubricants.

The work [1] reveals the achievements of modern scientists in the creation of environmentally friendly biodegradable lubricants. It is noted that the main problem is the development of a universal biodegradable base oil that could replace base mineral oils taking into account the preservation of the environment. The need for environmentally friendly products has been discussed for a long time in many forums. ASTM reviews the products available today and the tests required to determine performance criteria for biodegradable fluids. Synthetic fluids as a base oil have become widely used in a variety of industrial applications. Some of the applications include engine oils, transmission oils, hydraulic oils, compressor oils, pump and turbine oils. The choice of different base lubricants depends on the type of application, cost and biodegradability requirements. Vegetable oils are widely used for two-stroke systems, open gears, chain saws. For automotive lubricants with extended drain intervals, hydrotreated mineral oils are increasingly preferred. The development of chemically modified esters based on biological resources is a very profitable option for environmentally friendly applications. Development of synthetic esters from cost-effective sources for critical applications (automotive and industrial) is one of the best choices. Additionally, there is a need to develop hydrocarbon-based mineral oils with improved biodegradability and performance. Lubricants should be evaluated on the basis of increased thermal and mechanical stability, environmental safety and rapid biodegradability.

In the review [2], lubricants on a biological basis, various vegetable oils used as raw materials for the production of lubricants on a biological basis are considered in detail. The physical and chemical properties of biologically based lubricants are described. Features of the processes used for chemical modification of vegetable oils, lubricating properties of bio-based lubricants, as well as various additives to improve the properties of bio-based lubricants are highlighted. Vegetable oils have several advantages over conventional mineral oils, as they have a high level of biodegradability and are safe for the environment. The following methods of chemical modification of vegetable oils can be used to increase thermo-oxidative stability: transesterification, epoxidation or selective hydrogenation. The properties of biobased lubricants can also be improved by introducing additives: antioxidants, detergents and dispersants, nanoparticles, corrosion inhibitors, anti-seize additives and anti-wear additives. Bio-based lubricants appear to be promising alternatives for replacing petroleum-derived lubricants. Regarding the use of vegetable oils as lubricants on a biological basis, additional studies are being conducted to understand the lubrication mechanisms of these lubricants and their mixtures.

In [3], two main types of WCO treatment are discussed in detail: chemical transformations to utilize the chemical functional groups present in the waste, and physical treatments such as extraction, filtration and distillation procedures. The first part, which concerns chemical synthesis, is mostly related to the production of fuel. The second part, related to physical processing, focuses on the production of biolubricants. In addition, during the description of the filtration procedures, special attention is paid to the development and application of new materials and technologies for the treatment of WCO materials.

A technology based on a combination of water treatment and filtration on porous materials was made in [4], designing a mini-recycling plant aimed at the production of biolubricants from WCO (Fig. 1) [4].

The proposed technology can be described as follows: WCO is to be purified from water. The refined waste oil is then pushed to the filter module, where it is cleaned by a porous material. The combination of refining and filtration makes it possible to obtain purified processed vegetable oil.

Despite the results achieved in the field of filtration, further efforts are needed to improve performance and cost-effectiveness. In particular, careful research is needed to reduce the amount of oil absorbed by cellulose filters, to reduce the cost of synthesis and regeneration of synthetic materials.

In work [5], several types of cooking oil waste from various food establishments were investigated: a regular restaurant, a fast food restaurant, a fried food establishment, a mixture of used cooking oils of various unknown origins, without segregation

Oil has undergone molecular distillation. Distillation of WCO does not require too much energy, so it can be considered economically feasible. Molecular distillation yields two fractions: a lighter fraction enriched in free fatty acids, and a heavier fraction containing the most polar compounds and a low fraction of undistilled free fatty acids. Both fractions are liquid at room temperature.

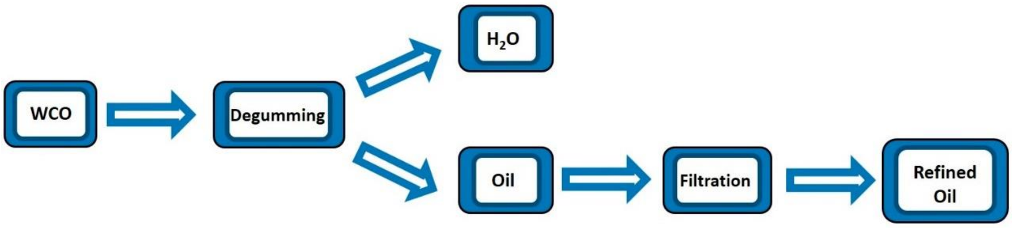


Fig. 1. WCO recycling process [4].

Studies of WCOs have shown marked variations in their chemical composition associated with several variables involved in the various roasting processes investigated. Deep-fried oils showed a high content of free fatty acids and diglycerides due to the hydrolysis of triglycerides [5]. In contrast, lightly roasted WCO showed rather low acidity, indicating a lower degree of hydrolysis. Variations in the chemical composition had different effects on the studied properties. WCO with the highest content of molecules (oligomers, dimers and polymers) showed the highest kinematic viscosity. WCOs with the highest values of total polar compounds and acidity showed the lowest viscosity index values, while WCOs with the lowest acidity values showed the highest viscosity index values and were less sensitive to temperature. revealed that acidity also affects the fluidity of oils at low temperature, so oils with the lowest acidity values have the best fluidity at low temperature. It was found that the high acidity and high ratio of unsaturated and saturated fatty acids of the oils gave these WCOs the greatest lubricating ability [5].

Molecular distillation was shown to yield two fractions, light and heavy, with significantly improved tribological properties compared to their parent waste cooking oil. Thus, the low viscosity and high polarity of the light fractions enriched with free fatty acids provide improved lubricating characteristics both in extreme and mixed modes of friction.

In the study [6] methylolpropane triester of fatty acid (TFATE) was obtained as a base oil of biolubricant material. This product was synthesized by transesterification of fatty acid methyl esters from waste cooking oil. The constituent reactions and oxidative stability of TFATE were analyzed. Under the selected conditions, TFATE was obtained with a yield of 85.7%. After purification by molecular distillation at 120 0C, the TFATE content in the product reached 99.6%. It has been proven that the chemical and physical properties of TFATE meet the requirements of ISO VG32.

A study [7] showed that WCO can be successfully hydrolyzed by Candida rugosa lipase to obtain FFA at an enzyme concentration of 1 g L-1 within 30 hours. The resulting FFA can be esterified with a higher alcohol (octanol) using Amberlyst 15H to produce an environmentally friendly bio-lubricant. It was found that temperature, amount of catalyst, molar ratio of reagents (alcohol : FFA) have a significant effect on the reaction rate. Complete recycling can be achieved in minimal time by using a suitable desiccant to remove the water produced during the esterification reaction. It can be concluded from the experiment that the most favorable conditions for the maximum conversion in the minimum time are the molar ratio octanol : FFA 3 : 1, temperature 80 ◦C, catalyst 2 g and desiccant (preferably silica gel powder) 50% by weight of FFA.

Studies have shown that esters based on olive oil have the highest thermal oxidation resistance due to the low content of polyunsaturated acids. While NPG esters have higher stability in thermo-oxidative conditions.

The polyols used during the transesterification process are NPG, TMP and PE. Each of them contains a different number of hydroxyl functional groups. In general, the viscosity of ester-based lubricants increases with polyol functionality. The number of hydroxyl groups affects the viscosity of esters in the following order: PE > TMP > NPG. Similarly, the viscosity of vegetable oil-based TMP esters is higher than that of equivalent esters, which may be due to the presence of three acidic groups in the ester structure.

The introduction of separation into methyl ether lowers the solidification temperature, disrupting the alignment and construction of hydrocarbon chains. This allows the oil to solidify at lower temperatures.

A specialized batch reactor (1.5 L) made of stainless steel was used to carry out esterification reactions under appropriate operating conditions (Fig. 2). The reactor was equipped with: a stirrer with an electric drive and a digital speed display (rpm); a thermostat that maintained the desired temperature of the liquid in the shirt; inlet channel for pouring the sample; sampling outlet equipped with a valve.

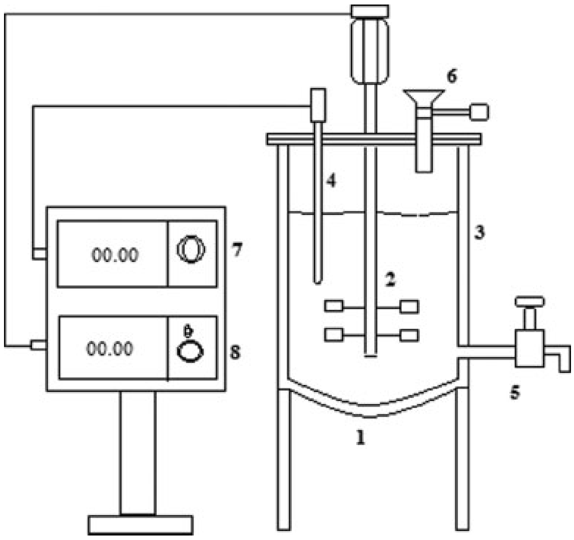


Fig. 2. Schematic diagram of the reactor for the esterification reaction: 1- reactor, 2- stirrer, 3- reactor casing, 4- thermocouple, 5- material output, 6 - material input, 7 - temperature indicator, 8- stirring speed indicator.

The review [8] describes in detail biological lubricants, various vegetable oils used as raw materials for the production of biolubricants, physicochemical properties of biological lubricants, processes used for chemical modification of vegetable oils. The properties of biolubricants are considered, as well as various additives used to improve the properties of biolubricants. Low temperature characteristics are the main limitation when it comes to the use of vegetable oils as lubricants. Although vegetable oils have strong intermolecular interactions that provide a strong lubricating film, these interactions also result in poor low-temperature properties.

The life cycle of lubricants obtained from renewable sources is shown in fig. 3 [8]. The main component of vegetable oils are triacylglycerols (98%), as well as various fatty acid molecules attached to the single structure of glycerol.

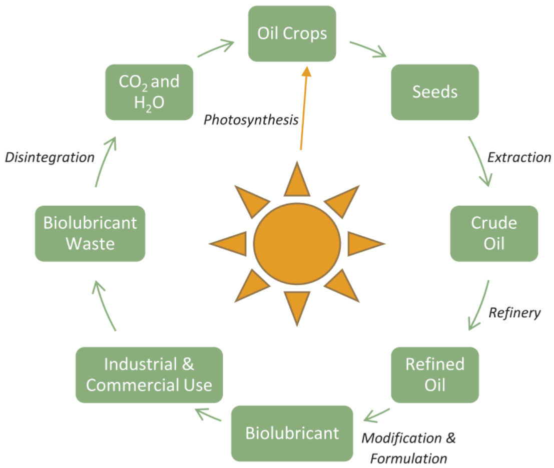


Fig. 3. Life cycle of biolubricants

Although the thermo-oxidative stability of vegetable oils can be a problem, this problem can be overcome by chemical modification of vegetable oils through transesterification, epoxidation or selective hydrogenation.

Sunflower oil is extracted from sunflower seeds and is usually used for cooking, as well as for the production of margarine and biodiesel. Sunflower oil is cheaper compared to olive oil. Sunflower varieties differ in the content of fatty acids [9-11]. Sunflower oil with a high oleic acid content has many properties that make it suitable for use in lubricants, with good oxidation resistance and lubricity. [9-11]. One study showed that high oleic sunflower oil (HOSO) can be used to replace mineral oils in textile and leather production without technical problems or equipment modification [11]. The correct composition of sunflower oil can be compared with mineral oil.

High oxidation resistance is an important criterion for lubricants, as low oxidation resistance will cause the lubricant to oxidize rapidly if left untreated. As a result, the lubricant thickens and polymerizes into a plastic consistency. Numerous studies were conducted to study the resistance of vegetable oils to oxidation [12-14]. The oxidation resistance of vegetable oils is generally lower than that of synthetic esters due to the higher degree of unsaturation in vegetable oils. Oxidation is undesirable because it leads to polymerization and degradation of the lubricant.

Attempts to improve the low-temperature properties and oxidation resistance of vegetable oils include transesterification of trimethylolpropane and methyl ether from vegetable sources [15–17]. Transesterification is a reaction in which a triglyceride molecule reacts with three moles of methanol in the presence of an acidic or basic catalyst [18-19], resulting in the formation of glycerol and mixtures of methyl esters of fatty acids.

The disadvantages of vegetable oils, such as low thermo-oxidative stability and cold flow, can also be enhanced by the use of additives. Manufacturers of different vegetable oils may choose different additives to meet the requirements of a particular application. For some oils, additives can be up to 5% (by weight). The presence of additives contributes to the improvement of the properties of lubricants and lubricants on a biological basis in terms of corrosion inhibition, as well as friction and wear characteristics. In general, esters with biodegradable additives have superior wear resistance compared to pure oils or blends of vegetable oils.

Antioxidants are used to slow down or prevent the oxidation process by slowing the oxidative degradation of the lubricant, while ensuring that the lubricant meets the technical requirements [20].

Nanoparticles are effective additives for lubricants and bio-based lubricants to reduce friction and wear. Nanoparticles are considered to be more effective compared to conventional additives for protection against high pressure and anti-wear additives due to their environmental properties [21]. The properties of biolubricants depend on the properties of the nanoparticles, such as the size, shape and concentration of the nanoparticles.

Friction in the contact of surfaces from the shear forces required to separate the interacting asperities. Friction and wear can be reduced by adding anti-wear and anti-seize additives to the oil. These additives create strong protective films on the metal surface, entering into a thermochemical reaction with the metal surface. Anti-seize and anti-wear additives usually contain chlorine, phosphorus and sulfur [22]. These elements protect the surface of the metal with layers of sulfides, chlorine, or phosphides that are easily erased, preventing severe galling and wear.

A fairly in-depth analysis of directions for processing used cooking oils is presented in the review [23]. It is noted thatthe use of biomass wastes such as used cooking oil (WCO) does not create competition and is a better source of resource recovery as it allows a second life cycle (Fig. 4).

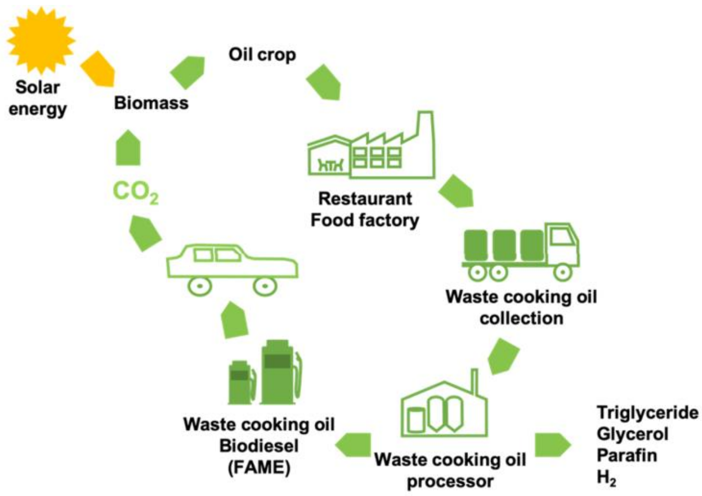


Fig. 4. Chain of cooking oil waste [23].

Valorization of WCO was realized by the following processes: transesterification, transesterification, hydrolysis, hydrodeoxygenation, hydrocracking and hydrogenation. Among them, transesterification is the main process that allows the production of biodiesel and bio-lubricant. Biodiesel can be obtained using heterogeneous catalysts having basic centers, acidic centers, a mixture of acidic and basic centers, or enzymes. Among heterogeneous catalysts, magnetic catalysts have been developed for easy separation of catalysts after each cycle. Homogeneous catalysts and enzymes as catalysts also allow the production of biodiesel. Various alternative technologies have been successfully studied, such as electrolysis, ultrasound, microwaves, continuous flow, even continuous flow with microwaves. Compared to transesterification, transesterification makes it possible to obtain biodiesel and triacetin instead of glycerol. Hydrolysis of WCO generates free fatty acids, glycerol, and water, while hydrogenation of WCO yields free fatty acids, free fatty aldehydes, free fatty alcohols, and alkanes via hydrodeoxygenation, hydrocracking using a similar petrochemical process.

In [24], used cooking oil is chemically modified to obtain biolubricants. Three WCO-based fluids were synthesized and considered as base lubricants for environmentally friendly lubricants. Typical properties of these biolubricants, such as viscosity, viscosity index, solidification temperature, cloud point. Corrosion resistance, oxidation resistance and four-ball anti-wear properties were investigated. WCO and its derivatives were tested for friction and wear reduction using a four-ball friction machine. Experimental results indicate that chemically modified WCOs are an economic, sustainable and ecological substitute for mineral oils and will find potential practical applications in the field of lubricants.

In order to reduce environmental pollution as a result of biolubricant synthesis, the study [25] developed an ecological and efficient strategy for the preparation of octylated biolubricant from waste cooking oil (WCO). First, it was hydrolyzed by lipase to obtain unsaturated fatty acids, and the latter were later concentrated by urea complexation. Further, new esters were synthesized by esterification with ethylhexanol using lipase, and new esters were additionally epoxidized. After that, the epoxy group was attacked with a reagent, octanoic acid, to obtain an octylated biolubricant. Articles [26-27] review recent advances in the synthesis of biolubricants from vegetable oils using chemical modification methods, such as esterification/reesterification,

Conclusions

An overview of the basic properties of biologically based lubricants, the role of chemical functionality and additives, as well as their relationship with the effectiveness of the lubricant is presented. Vegetable oils have several advantages over conventional mineral oils, as they are biodegradable and safe for the environment. Although the thermo-oxidative stability of vegetable oils may be insufficient, this problem can be overcome by chemical modification of vegetable oils by transesterification, epoxidation or selective hydrogenation. The properties of bio-based lubricants can also be improved by adding additives such as antioxidants, detergents and dispersants, viscosity modifiers, nanoparticles, corrosion inhibitors, extreme pressure and anti-wear additives.

References

1. Ponnekanti Nagendramma, Savita Kaul, Development of ecofriendly/biodegradable lubricants: An overview, Renewable and Sustainable Energy Reviews, Volume 16, Issue 1, 2012, Pages 764-774, https://doi.org/10.1016/j.rser .2011.09.002.

2. NA Zainal, NWM Zulkifli, M. Gulzar, HH Masjuki, A review on the chemistry, production, and technological potential of bio-based lubricants, Renewable and Sustainable Energy Reviews, Volume 82, Part 1, 2018, Pages 80-102 ,https://doi.org/10.1016/j.rser.2017.09.004.

3. Mannu, A., Garroni, S., Ibanez Porras, J., & Mele, A. (2020). Available Technologies and Materials for Waste Cooking Oil Recycling. Processes, 8(3), 366. MDPI AG. Retrieved fromhttp://dx.doi.org/10.3390/pr8030366

4. Mannu, A.; Ferro, M.; Colombo Dugoni, G.; Panzeri, W.; Petretto, GL; Urgeghe, P.; Mele, A. Recycling of Waste Cooking Oils: Variation of the Chemical Composition during Water Treatment. Preprints 2019, 160, 842–847.https://www.sciencedirect.com/science/article/pii/S1876610219312366?via%3Dihub

5. SD Fernández-Silva, MA Delgado, MV Ruiz-Méndez, I. Giráldez, M. García-Morales, Potential valorization of waste cooking oils into sustainable bio-lubricants, Industrial Crops and Products,Volume 185,2022,115109,https ://doi.org/10.1016/j.indcrop.2022.115109.

6. Wang E, et al., Synthesis and oxidative stability of trimethylolpropane fatty acid triester as a biolubricant base oil from waste cooking oil, Biomass and Bioenergy (2014),http://dx.doi.org/10.1016/j.biombioe.2014.03.022.

7. Chowdhury, A., Mitra, D., & Biswas, D. (2013). Biolubricant synthesis from waste cooking oil via enzymatic hydrolysis followed by chemical esterification. Journal of Chemical Technology & Biotechnology, 88(1), 139-144.https://doi.org/10.1002/jctb.3874

8. A. Zainal, NWM Zulkifli, M. Gulzar, HH Masjuki, A review on the chemistry, production, and technological potential of bio-based lubricants, Renewable and Sustainable Energy Reviews, Volume 82, Part 1, 2018, Pages 80- 102, https://doi.org/10.1016/j.rser.2017.09.004.

9. Minami I, Hong HS, Mathur NC. Lubrication performance of model organic compounds in high oleic sunflower oil. J Syn Lubr 1999;16:1–12.

10. Quinchia LA, Delgado MA, Valencia C, Franco JM, Gallegos C. Viscosity modification of high-oleic sunflower oil with polymeric additives for the design of new biolubricant formulations. Environ Sci Technol 2009;43:2060–5.

11. Lazzeri L, Mazzoncini M, Rossi A, Balducci E, Bartolini G, Giovannelli L, et al. Biolubricants for the textile and tannery industries as an alternative to conventional mineral oils: an application experience in the Tuscany province. Ind Crops Prod 2006;24:280–91.

12. Erhan SZ, Sharma BK, Perez JM. Oxidation and low temperature stability of vegetable oil-based lubricants. Ind Crops Prod 2006;24:292–9.

13. Kodali DR. High performance ester lubricants from natural oils. Ind Lubr Tribol 2002;54:165–70.

14. Frega N, Mozzon M, Lercker G. Effects of free fatty acids on oxidative stability of vegetable oil. J Am Oil Chem Soc 1999;76:325–9.

15. Hamid HA, Yunus R, Rashid U, Choong TSY, Al-Muhtaseb AaH. Synthesis of palm oil-based trimethylolpropane ester as potential biolubricant: chemical kinetics modeling. Chem Eng J 2012;200–202:532–40.

16. Salimon J, Salih N, Yousif E. Synthesis, characterization and physicochemical properties of oleic acid ether derivatives as biolubricant base stocks. J Oleo Sci 2011;60:613–8.

17. Salimon J, Salih N, Yousif E. Triester derivatives of oleic acid: the effect of chemical structure on low temperature, thermo-oxidation and tribological properties. Ind Crops Prod 2012;38:107–14.

18. Leung DYC, Wu X, Leung MKH. A review on biodiesel production using catalyzed transesterification. Apple Energy. 2010;87:1083–95.

19. Madankar CS, Pradhan S, Naik SN. Parametric study of reactive extraction of castor seed (Ricinus communis L.) for methyl ester production and its potential use as bio lubricant. Ind Crops Prod 2013;43:283–90.

20. Wanasundara PKJPD, Shahidi F. Antioxidants: science, technology, and applications. bailey's industrial oil and fat products. John Wiley & Sons, Inc.; 2005.

21. Alves SM, Barros BS, Trajano MF, Ribeiro KSB, Moura E. Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions. Tribol Int 2013;65:28–36.

22. Canter N. Special report: trends in extreme pressure additives. Tribol Lubr Technol 2007;63:10–7.

23. Mohamad R. Khodadadi, Irene Malpartida, Chi-Wing Tsang, Carol Sze Ki Lin, Christophe Len, Recent advances on the catalytic conversion of waste cooking oil, Molecular Catalysis, Volume 494, 2020, 111128,https://doi.org/10.1016/j.mcat.2020.111128.

24. Weimin Li, Xiaobo Wang, Bio-lubricants Derived from Waste Cooking Oil with Improved Oxidation Stability and Low-temperature Properties, Journal of Oleo Science, 2015, Volume 64, Issue 4, Pages 367-374, Released on J-STAGE April 01, 2015, Advance online publication March 11, 2015,https://doi.org/10.5650/jos.ess14235

25. Zhang W, Ji H, Song Y, Ma S, Xiong W, Chen C, Chen B, Zhang X, Green preparation of branched biolubricant by chemically modifying waste cooking oil with lipase and ionic liquid, Journal of Cleaner Production,https://doi.org/10.1016/j.jclepro.2020.122918.

26. Josiah McNutt, Quan (Sophia) He, Development of biolubricants from vegetable oils via chemical modification, Journal of Industrial and Engineering Chemistry, Volume 36, 2016, Pages 1-12,https://doi.org/10.1016/j.jiec.2016.02.008

27. Sarno, M., Iuliano, M., Cirillo, C., 2019. Optimized procedure for the preparation of an enzymatic nanocatalyst to produce a bio-lubricant from waste cooking oil. Chem. Eng. J. 377, 120273. https://doi.org/10.1016/j.cej.2018.10.210.

Диха О., Гетьман М., Старий А., Калачинський Т. Огляд аспектів переробки і застосування відпрацьованих кулінарних олив як ефективних мастильних матеріалів

У зв'язку із забрудненням навколишнього середовища та виснаженням запасів нафти мастила на біологічній основі викликають великий інтерес як заміна мастилам на основі мінеральних масел. Біомастила мають низку переваг перед мінеральними мастильними матеріалами, включаючи високу здатність до біологічного розкладання, низьку токсичність, змащувальні властивості та мінімальний вплив на навколишнє середовище. У представленому огляді описано основні характеристики та властивості біологічних мастил, різноманітних рослинних олій, які використовуються як сировина для виробництва біомастильних матеріалів. Проаналізовано фізико-хімічні властивості біологічних мастил з точки зору поліпшення. Визначено технологічні процеси хімічної модифікації рослинних олій, що забезпечують змащувальні та протизносні властивості отриманих біомастильних матеріалів. Також рекомендуються різні добавки, що використовуються для поліпшення властивостей біомастильних матеріалів. Цей оглядовий матеріал надасть дослідникам і практикам додаткову інформацію про практику використання біомастильних матеріалів.

Ключові слова: рослинні олії, відходи харчової промисловості, екологічність, хімічна модифікація, фізична обробка, змащення, зносостійкість.

Problems of Tribology, V. 28, No 2/108-2023

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribology@khmnu.edu.ua

INFORMATION ABOUT JOURNAL"PROBLEMS OF TRIBOLOGY"

POLICY (GOAL AND TASKS)

"Problems of Tribology (Problems of Tribology)" - an international scientific journal.

Along with the main task of collecting information from tribology, the journal also performs organizational and coordinating functions:

- coordination of scientific and technical work in the field of tribology;
- organization of conferences, sympsiums;
- organization of work on the creation of databases and expert systems in the field of tribology;
- the organization of communications and information exchange between specialists in the field of tribology internationally.

2. The journal contains articles directly or indirectly related to tribology, including:

- theoretical problems (physics, chemistry, mechanics, mathematics)
- experimental methods and research results;
- contact mechanics, friction, wear, lubrication, durability and reliability of friction units of machines and units;
- scientific, technical and production problems of manufacturing, repair, improving the quality, reliability and durability of friction;
- technological and structural methods of improving wear resistance, frictional and anti-friction properties of friction units;
- problems of tribo materials science;
- methodological and methodological issues of training specialists in tribology.

3. The main requirements of the article is the novelty and completeness of information.

Articles of theoretical content should include theoretical explanation (possibly in the form of an annex to the article) to assess the scientific novelty of the publication.

Experimental articles should contain complete information about the methodology, conditions and results of the experiment.

Technological profile articles should contain a description of the technology as much as possible. If it is impossible to disclose "know-how", the method of obtaining the necessary detailed information must be indicated.

4. All articles are reviewed by a closed double review for compliance with the topics and level requirements. At the same time, the authors are fully responsible for the content of the articles.

5. Due to the international nature of the journal it is preferably submit articles in English.

REQUIREMENTS TO THE ARTICLES

In order to publish an article in the journal authors should submit it by e-mail.

Text of an article should be laid out on A4 format (210 x 297 mm) page with the following margins set: left and right – 2.0 cm, top and bottom – 2.5 cm. Use the font Times New Roman throughout, single-spacing, 10-point type and 1.0 cm indention for body text. Use lower-case bold 14-point type for headings. Put subheadings in bold.

Article structure:

– Universal Decimal classification index (in the upper left corner).
– Initials and surnames of all authors (no more than 4 people) and the article title (up to 10 words) in Ukrainian, Russian and English (one-column format).
– Abstract (200–300 words, only commonly accepted terminology) in Englishshould be structured and contain the following elements: purpose, methodology, findings, originality, practical value, keywords (6–8 words), one-column format. The abstract should not repeat the heading of the article.
– Body text.
– Reference list.
– Abstracts and keywords (up to 6–8words) in the Ukrainian and Russian languages;

Each article should include the following sections:

– An introduction, indicating article’s scientific problem.
– An analysis of the recent research and publications.

– Unsolved aspects of the problem.
– Objectives of the article.
– Presentation of the main research and explanation of scientific results.
– Research conclusions and recommendations for further research in this area.
– The title and number of the project in terms of whichthe presented results were obtained and Acknowledgements to the organizations and/or people contributing to or sponsoring the project (at the discretion of the author)

The recommended length of articles (including text, tables, and figures) is 6–9 pages. Figures should not exceed 25 % of length of an article. The text should be laconic, and should not contain duplicated information. No running titles and section brakes should be applied in the file.

Figures must be provided both in color and grayscale. They must be included in the text after corresponding references and given as separate files TIFF, JPG. EPS (300 dpi). The preferable width for the figures is 8.15 cm; not more than 17 cm for maps, charts, etc. All figures should be placed within the text, not in tables. Lettering, lines and symbols must be readable. Captions under the figures should contain order number and description of the figure and should be put in Italics. Placing the figure numbers and captions inside figures is not allowed.

Equationsshould be entered using Microsoft Word for Windows Editor plug-in or Microsoft Equation, 10-point type. The equations sited in the text are to be numbered in order of their appearance in the text (number in brackets with right justify). Equations should be column width (<8 cm). Long formulas should be divided into parts of 8 cm width. Before and after each formula there should be one empty line. Physical quantities should be measured in SI units. An integer part should be separated from a decimal by a dot.

Tablesmust be in portrait orientation, have titles and be numbered. Preferably tables should not exceed 1 page in length; width should make 8.15 cm or 17 cm. It is recommended to use 8–9-point type (not smaller than 6-point type for big data).

References(no more than 15 items, published not earlier than 5 years before, no more than 20%of self-citations) should be listed in the order of appearance in the text of the article. The in-text references should be given in square brackets.

Also the author should submit the following data about all authors of the article: surname, name and patronymic, academic degree, academic rank, place of employment (complete name of organization), position, city, country, phone number, e-mail and authors' ORCID identifier, in a separate file in English, Ukrainian and Russian (one-column format, comma-separated).

REVIEW PROCEDURE

All manuscripts are initially treated by editors to assess their compliance with the requirements of the journal and the subject.

After the editor decision the manuscripts are sent to at least two external experts working in this area. **The manuscript goes double-blind peer review**, neither the authors nor the reviewers do not know each other.

Review comments transmitted to the author, together with a recommendation for a possible revision of the manuscript. Publishing editor reports to the authors about adopting manuscript without require revision or authors are given the opportunity to review the manuscript and submit it again, or manuscript rejected.

EDITORIAL ETHICS

Principles of professional ethics in the work of the editor and publisher

The editor of a peer-reviewed journal is responsible for deciding which of the articles submitted to the journal should be published. The validation of the work in question and its importance to researchers and readers must always drive such decisions.

- An editor should make decisions on which articles to publish based on representational faithfulness and scholarly importance of the proposed work.
- An editor should be alert to intellectual property issues and must not to publish information if there are reasons to think that it is plagiarism. ·
- An editor should evaluate manuscripts for their intellectual content without regard to race, gender, sexual orientation, religious belief, ethnic origin, citizenship, social set-up or political philosophy of the authors.
- Unpublished materials disclosed in a submitted manuscript must not be used in an editor's own research without the express written consent of the author. Privileged information or ideas obtained through peer review must be kept confidential and not used for personal advantage.
- An editor should take reasonably responsive measures when ethical complaints have been presented concerning a submitted manuscript or published paper, in conjunction with the publisher (or society). Every reported act of unethical publishing behavior must be looked into, even if it is discovered years after publication.

Publishers should provide reasonable practical support to editors and define the relationship between publishers, editor and other parties in a contract.

- Publishers should protect intellectual property and copyright.

- Publishers should foster editorial independence.

- Publishers should work with journal editors to set journal policies appropriately and aim to meet those policies, particularly with respect to editorial independence, research ethics, authorship, transparency and integrity (for example, conflicts of interest research funding, reporting standards), peer review and the role of the editorial team beyond that of the journal editor, appeals and complaints.

- Publishers should communicate and periodically review journal policies (for example, to authors, readers, peer reviewers).

- Publishers should assist the parties (for example, institutions, grant funders, governing bodies) responsible for the investigation of suspected research and publication misconduct and, where possible, facilitate in the resolution of these cases.

- Publishers are responsible for publishing corrections, clarifications and retractions.

Ethical principles in the reviewer work

Peer review assists the editor in making editorial decisions and through the editorial communications with the author may also assist the author in improving the paper. That is why actions of a reviewer should be unbiased.

- Any manuscripts received for review must be treated as confidential documents. They must not be shown to or discussed with others except as authorized by the editor.

- Reviews should be conducted objectively. Personal criticism of the author is inappropriate. Referees should express their views clearly with supporting arguments.

- Unpublished materials disclosed in a submitted manuscript must not be used in a reviewer's own research without the express written consent of the author. Privileged information or ideas obtained through peer review must be kept confidential and not used for personal advantage.

- Any selected referee who feels unqualified to review the research reported in a manuscript or knows that its prompt review will be impossible should notify the editor and excuse himself from the review process.

Principles that should guide the author of scientific publications

Authors realize that they are responsible for novelty and faithfulness of research results.

- Authors of reports of original research should present an accurate account of the work performed as well as an objective discussion of its significance. Underlying data should be represented accurately in the paper. A paper should contain sufficient detail and references to permit others to replicate the work. Fraudulent or knowingly inaccurate statements constitute unethical behavior and are unacceptable.

- An author should ensure that they have written entirely original works, and if the author has used the work and/or words of others, then this has been appropriately cited or quoted. Plagiarism in all its forms constitutes unethical publishing behavior and is unacceptable.

- Proper acknowledgment of the work of others must always be given. Author should cite publications that have been influential in determining the nature of the reported work. Information obtained privately, as in conversation, correspondence, or discussion with third parties, must not be used or reported without explicit, written permission from the source. Information obtained in the course of confidential services, such as refereeing manuscripts or grant applications, must not be used without the explicit written permission of the author of the work involved in these services.

- An author should not in general publish manuscripts describing essentially the same research in more than one journal or primary publication. Submitting the same manuscript to more than one journal concurrently constitutes unethical publishing behavior and is unacceptable. In general, an author should not submit for consideration in another journal a previously published paper.

- All those who have made significant contributions should be listed as co-authors. Where there are others who have participated in certain substantive aspects of the research project, they should be acknowledged or listed as contributors. The corresponding author should ensure that all co-authors have seen and approved the final version of the paper and have agreed to its submission for publication.

- When an author discovers a significant error or inaccuracy in their own published work, it is the author's obligation to promptly notify the journal editor or publisher and cooperate with the editor to retract or correct the paper. If the editor or the publisher learns from a third party that a published work contains a significant error, it is the obligation of the author to promptly retract or correct the paper or provide evidence to the editor of the correctness of the original paper.

CONTACTS

International scientific journal “Problems of Tribology”,
Khmelnitsky National University,
Institutskaia str. 11, Khmelnitsky, 29016, Ukraine
phone +380975546925
E-mail: tribosenator@gmail.com
Internet: http://tribology.khnu.km.ua