The State Scientific Institution
"V.A. Belyi Metal-Polymer Research Institute
National Academy of Sciences of Belarus"

International Seminar «Tribology at the Silk Belt 2019»

Abstracts

June 24–26, 2019, Gomel, Belarus

清華大學
Tsinghua University

State Key Laboratory of Tribology, Tsinghua University

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The book includes the proceedings of the 1th international seminar **“Tribology at the Silk Belt 2019”** in the fields of friction and wear.

International Seminar
"Tribology at the Silk Belt 2019"

June 24–26, 2019, Gomel, Belarus

National Academy of Sciences, Minsk, Belarus
Tsinghua University, Beijing, China

Organizers of the Seminar:

Metal-Polymer Research Institute of NASB, Gomel
Professor Andrei Y. GRIGORIEV, Director of MPRI NASB
aygri@tut.by.

State Key Laboratory of Tribology, Beijing
Professor Yonggang MENG, Director of SKLT
mengyg@tsinghua.edu.cn

Seminar Program Coordinator:
Academician Nikolai K. MYSHKIN, Head of Tribology Department, MPRI
nkmyshkin@mail.ru , nkmyshkin@mpri.org.by

Scientific Secretary;
Dr. Inna N. KAVALIOVA, Coordinating Editor, Journal of Friction and Wear,
silk-belt-19@mpri.org.by
Tel: +375 (232) 34 06 36, 34 17 12
Fax: +375 (232) 34 17 11

Objectives:

Countries of the ancient Silk Belt have large and developed national tribology communities and significant advances in basics and applications of friction, lubrication, and wear research. The seminar objectives are the exchange of knowledge and potential cooperation ideas between the representatives of Eurasian tribology research centers. Such topics as prospective materials, coatings and lubricants for energy-saving and ecologically friendly tribosystems (green tribology) are welcome for presentations. Due to a great scale of the applications the aspects of tribology in various types of transportation, wear monitoring, and surface engineering can be of special interest, as well as the environmental factors and the effects of extreme operation conditions on tribosystem behavior.

Seminar Location

Sessions of the seminar will be located in the countryside of Gomel. It is a regional center with population of 500 thousand people and second industrial and research center of Belarus Republic locating three research institutes of the NASB and six universities.

Metal-Polymer Research Institute of NASB was established in 1959 by academician Vladimir A. Belyi. It has 5 research departments and Special Design Bureau and pilot manufacturing plant. The total staff of MPRI includes about 200 people with 8 professors and 26 PhDs.

Time Limits:

Presentations:

– plenary – 30 min with discussion
– session – 20 min with discussion

Working Language — English

Greeting Address from the President
of International Tribology Council
Prof. Ali Erdemir

International Tribology Council

Administered by:
Jost Institute for Tribotechnology,
University of Central Lancashire
Preston PR1 2HE
Lancashire, UK
Tel: +44 1772 893322
Fax: +44 1772 892915
Email: lsherrington@uclan.ac.uk

www.itctribology.net

May 30, 2019

Dear Chairman, Organizing Committee, and the Participants of the Tribology of the Silk Belt 2019 Seminar:

It is with great pleasure that I offer my sincere congratulation to all of you for organizing this very momentous event in Gomel. I also thank the participants who are attending from all of the Silk Belt countries that played pivotal roles in expanding international trade, cultural and scientific exchanges for many Centuries. It is important to remember that ancient tribologists of that time have pioneered many critical innovations which positively impacted our modern day tribology in a very remarkable way all over the world. Specifically, without those very resilient wheels, ropes, and textiles, these long-enduring exchanges would have been impossible. Modern day tribology, which has recently celebrated its 50th anniversary in Buckingham Palace in London, can trace its foundations to the many critical innovations generated by the Silk Road traders. Today, our role remains the same. Specifically, we must still keep the wheels and gears of modern machinery rolling in an ecologically and environmentally sustainable manner.

From the very rich and diverse program of the Silk Belt 2019 Seminar, I am very pleased to see that many diverse areas of our profession will be represented and the many challenges that we face today will be addressed. In closing, I offer my sincere thanks and congratulations to all of you. I have no doubt that the outcome of this historical event will enhance our knowledge base further and strengthen our resolve to preserve this beautiful planet for future generations to come.

Thank you.

Sincerely,

Ali Erdemir

Ali Erdemir, Ph.D.
President of the International Tribology Council

CONTENTS

ACTUAL PROBLEMS IN TRIBOLOGY

N.K. Myshkin and A.Ya. Grigoriev

Metal-Polymer Research Institute of NASB, Gomel, Belarus, nkmyshkin@mpri.org.by

Keywords: tribology; deformation; adhesion; scale factor; texture.

Half a century of tribology was celebrated on March 2, 2016 on the anniversary of the Working Group report (Jost report) which has started tribology development as a multidisciplinary subject including mechanics, surface physics, and chemistry. Nowadays it was developed to many other areas as biology, medicine, and ecology [1, 2].

Theory of friction was developed in two aspects: mechanical (deformation) and molecular (adhesion) [3, 4]. Still the general theory is not completed. The reason is the complexity of friction phenomena and its multi-scale nature [5].

Surface geometry and nominal normal load are considered as the key factors determining the contact deformation in a tribosystem, but contact area and pressure definitions are scale-dependent. Adhesion is another key scale-dependent factor and it strongly affects friction. Origin of surface forces is a combination of phenomena acting at various scales and being of different physical nature. Heat generation at friction is also scale-localized factor as it relates to flash, surface, and volume sources of heat generation relating to various mechanisms.

The absence of general theory has not stopped the development of the efficient tribosystems based on novel design, lubricants, materials, and coatings. The impact of tribology development on global economy and ecology is estimated by huge figures [6]. The certain lack of friction theory was compensated by tests of materials, lubricants, and components under laboratory, bench, and real conditions.

Any friction and wear model should consider topography parameters. Superposition of deviations of different origins means that surface reliefs in various scales are also different. It has become clear recently that it is necessary to characterize the surface as an object having a certain pattern and in tribology this approach is presented with the concept of texture [7] Concept of texture has brought the 3-D presentation of the real surface, and using the image analysis provides the possibility of digital presentation of surfaces and their analysis.

Contact mechanics is developing quickly and solutions of contact problems were found with taking account of adhesion, roughness, mutual influence of real contact spots, and scale factor [8, 9]. Molecular dynamics methods are steadily improving and it is possible to widen the scale of friction contact simulation for large combinations of atoms and molecules. In near future the progress in computers and nanotribology provides the hope for developing analytical models more adequate to real tribosystems.

Progress in material science has brought the development of more efficient materials, coatings, and lubricants. Technologies of surface engineering have given possibilities to produce surface layers and structures modified for certain practical tasks with low and high friction at necessary wear resistance. The data on the energy losses in motor cars related to friction coefficient have shown dramatic drop from 2000 to 2010 and the forecast looks even more optimistic for 2020. Similar optimism is demonstrated in forecast of friction reduction savings in trucks and buses, mining machines, and paper making machines [6].

In engineering tribology we need to mention the progress in methodology and hardware of tests for friction and wear. The interpretation of the test data needs complicated computations and design of databases supplied by data from real operation of machines. The task of the test data treatment can be solved efficiently while using the estimates of parametrical equivalence of the laboratory test and real operation conditions. The image processing and machine vision technology give possibility for adequate analysis of morphology of worn surfaces and wear debris with further collection of wear atlases. Wear monitoring systems are becoming intelligent and their progress provides the transition to predictive maintenance correcting the system operation to sustainable state [10].

Until the last century vegetable oils and animal fat were most common lubricants. Development of the additives to mineral oils has made them dominant in industry. In the 1990-ies ecological laws start to limit the use of mineral oils in agriculture and forestry. In 2003-2009 the approval of EU directives and road maps in "green technology" has initiated the promotion of vegetable oils [11]. Nowadays more than 150 brands of lubricating oils and working fluids are produced commercially on the base of vegetable raw materials.

Good prospects are open in green tribology by the biodegradable polymer composites and nanocomposites with natural fillers. For example, there is an interest to thermoplastic matrices with nanoclay fillers which have potential for many applications [12]. Biodegradable polymers are also promising from the point of view of ecology.

Science of friction, lubrication, and wear has grown from the ancient and medieval roots to industrial revolution and current technological transformations. Being formulated as "tribology" it has got a new impulse as a multidisciplinary concept. We have a plenty evidences of its economic value for industrial society with other great signs of social and ecological impact.

Probably, we will not see the universal theory of friction efficient at all the scales of contact interactions and easily applicable to engineering problems, but methods of tribosystem simulation are developing quickly due to progress in computing, and accuracy in analytical techniques. The old methods of inclined plane, pendulum, and feedback balance with modern systems of measurement can give more data for experimental tribology. Estimation of the effect of tribofilms can provide more insight to adhesion nature. The tests estimating the stability of friction coefficient at different normal loads and stiffness of measuring systems can provide limits for tribotesting applicability to practice.

The global information exchange and cooperation is increasing rapidly with world congresses getting together thousands of experts and publication of hundreds of journals and books in the field. International Tribology Council has more than 40 national societies worldwide.

Acknowledgements This work was partially funded by Belorussian Republican Foundation for Fundamental Research (grant No T18P-061).

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ADVANCES OF SUPERLUBRICITY

Jianbin Luo

State Key Laboratory of Tribology, Tsinghua University, Beijing, China, luojb@tsinghua.edu.cn

Introduction. Superlubricity has developed very fast in recent years as a new and an important area in tribology. Many new phenomena, new materials, and new mechanism both in liquid and solid superlubricity have been obtained. In the liquid area, a new system of superlubricity liquids with new mechanism has been found, which exhibits very good properties of superlubricity under the higher pressure. In solid area, more materials in superlubricity have been observed both by experiment and the molecular dynamics simulation (MDS), such as grapheme to grapheme surfaces, highly oriented pyrolytic graphite (HOPG) to grapheme etc. Mechanism for different tribo-systems has been discussed.

Liquid Superlubricity. ***Superlubricity of mixture of acid and polyhydroxy alcohol.*** The acid solution has been found having superlubricity properties between glass plate and Si_3N_4 ball in our group in 2010 [1–3]. The superlubricity was achieved after a running-in process [4]. Li et al. [5] found superlubricity is related to hydrogen ions and proposed that the existence of hydrogen bond network among H_3PO_4, $H_2PO_4^-$ and H_2O is in favor of getting superlubricity. Based on such assumption, most acid solutions mixed with polyhydroxy alcohol have been found to realize the superlubricity, as shown in Fig. 1.

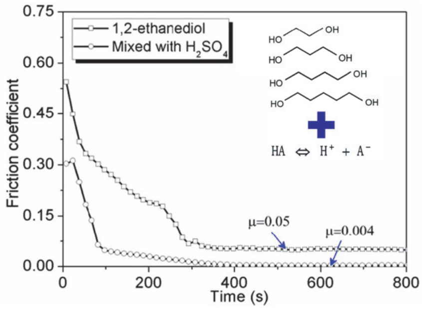

Fig. 1. The friction coefficient with time [5]

Superlubricity mechanism of the mixture of acid and polyhydroxy alcohol. In order to understand the superlubricity mechanism the mixture of acid and polyhydroxy alcohol, based on the film thickness measured, variation of the lubrication regime has been investigated in the running-in process. Experiments indicate that mixed lubrication is changed into thin film lubrication in the superlubricity state in the running-in period [6]. The acid solution in the running-in process plays the key role on achieving superlubricity. A superlubricity mechanism was proposed as shown in the inset of Fig. 2 [7]. The superlubricity is attributed to the ability of the acid to (i) provide favorable conditions for thin film lubrication, and (ii) generate a repulsive double-layer force through the adsorption of hydrogen ions on the friction surfaces.

Superlubricity of PAO oils with running-in by acid. There is a question of whether superlubricity can be achieved using oil-based lubricants. A novel approach was approached, that the superlubricity of silicone oil can be achieved between tribo-surfaces (Si_3N_4/glass) by running-in with an acid solution [8]. As shown in Fig. 3, the friction coefficient of silicone oil (100) after the running-in with acid can be reduced to about 0.004, which is only one-thirtieth of its original value ($\mu = 0.13$).

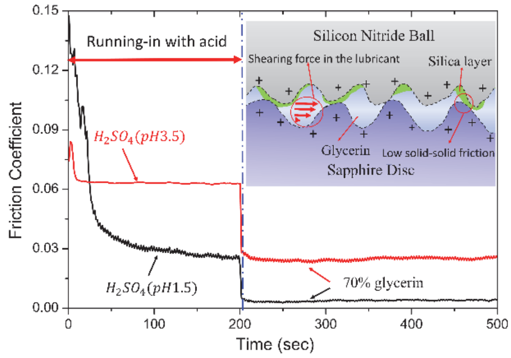

Fig. 2. Friction coefficient of the glycerin solution (70%) after the running-in process with sulfuric acid. The inset shows the schematic illustration of the superlubricity model [7]

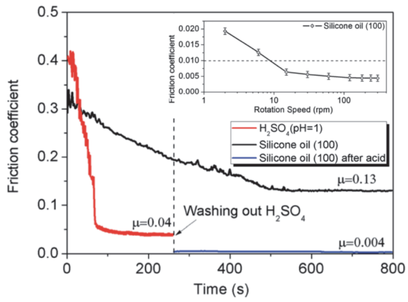

Fig. 3. Friction coefficient of silicone oil and that after running-in process with H_2SO_4 [8]

Solid Superlubricity. ***2D Material as based lubricants.*** Recently, Ge X. et al. [9] in our group achieved a macroscale superlubricity state through the synergy effect of graphene-oxide nanoflakes (GONFs)prepared via a modified Hummers method and ethanediol (EDO) at a Si_3N_4/SiO_2 tribopair. GONFs were 0.8 nm thick, had an interlayer spacing of 0.45 nm, and had an oxygen content of 30–40%, as depicted in Fig. 4a–e. The results for the friction and wear of GONFs-EDO are depicted in Fig. 4f–g. The COF of GONFs-EDO decreased to less than 0.01 after the wearing-in period of 600 s; and then to 0.0037 remaining stable for 2 h. Furthermore, the wear results show that the wear volume of the ball under lubrication with GONFs-EDO (5.1 × 104 μm^3) was only 5% of that of the ball under lubrication with EDO (1.3 × 106 μm^3). These results indicate the excellent superlubricity and anti-wear performances of GONFs-EDO. GONFs were adsorbed on the surfaces of the tribopair (Fig. 4h), preventing direct contact between asperities. The super-low shear stresses between the GONFs interfaces contributed to the superlubricity and super-low wear, as depicted in Fig. 4i. Moreover, the formation of the GONFs-EDO hydrated network and the partial-slip boundary condition at the GONFs-EDO interface contributed to the super-low shear stresses of the liquid layer, leading to superlubricity, as depicted in Fig. 4j.

Superlubricity of graphene-coated microsphere. More solids have been found in superlubricity state in recent years [10–12]. In our group, a direct measurement of sliding friction between graphene and graphene, and between graphene and hexagonal boron nitride (h-BN) under high contact pressure has been achieved by employing a graphene-coated microsphere (GMS) probe prepared by a metal-catalyst-free chemical vapor deposition method, as shown in Fig. 5 [12]. The exceptionally low and robust friction coefficient of 0.003 is accomplished. Moreover, the superlubricity has been achieved under the asperity contact pressure up to 1 GPa and is insensitive to relative humidity up to 51% RH. This ultralow friction is attributed to the sustainable overall incommensurability due to the multi-asperity contact covered with randomly oriented graphene nano-grains. This realization of microscale superlubricity can be extended to the sliding between varieties of two-dimensional (2D) layers.

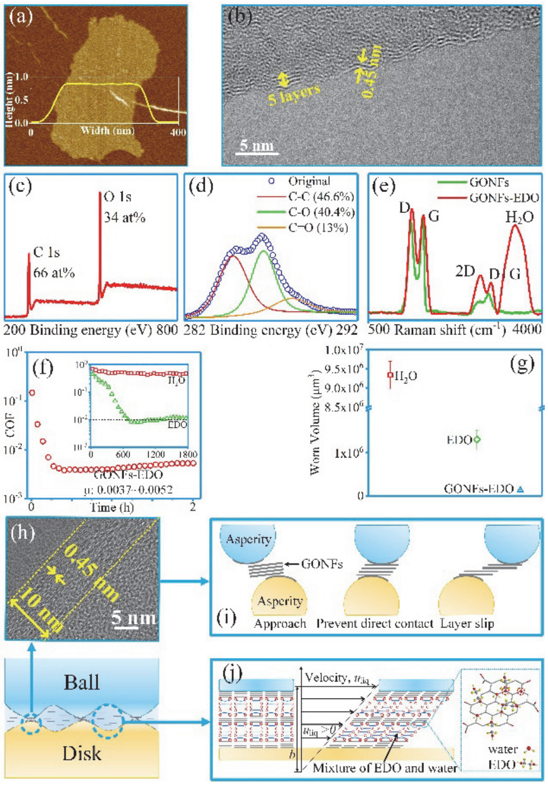

Fig. 4. Characterization of GONFs: (a) atomic force microscopy image; (b) high-resolution transmission electron microscopy (HRTEM) image; (c, d) XPS spectra; (e) Raman spectra. (f, g) Friction and wear testing results for GONFs-EDO. (h) HRTEM image of the cross-sectional area of the worn surface. (i, j) Proposed superlubricity and anti-wear mechanism of GONFs-EDO [9]

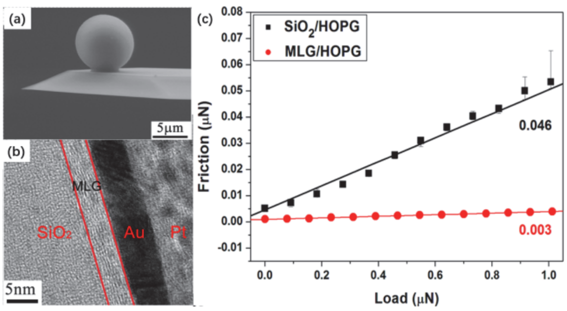

Fig. 5. (a) SEM side view of the graphene-coated microsphere probe. (b) Pt and Au films are deposited as the protective film during TEM sample preparation of focused ion beam process. (c) Friction force as a function of the applied normal load for SiO_2 microsphere sliding against HOPG and MLG-coated SiO_2 microsphere against HOPG respectively [12]

In 2018, Y. Liu et al. in our group propose an approach of thermally assisted mechanical exfoliation and transfer to fabricate various 2D flake-wrapped atomic force microscopy (AFM) tips and to directly measure the interlayer friction between 2D flakes in single-crystalline contact. A superlow friction coefficient about $1{\cdot}10^{-4}$ between different 2D flakes and layered bulk materials is achieved as shown in Fig. 6. The rotation angle dependence of superlubricity is observed for friction between graphite layers, whereas it is not observed between graphite and h-BN because of the incommensurate contact of the mismatched lattices.

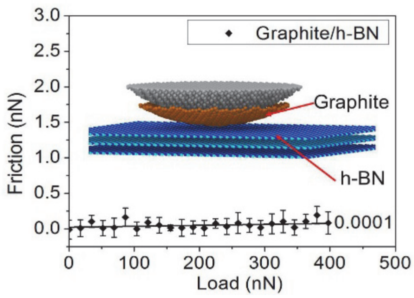

Fig. 6. Friction coefficient between graphite and h-BN [13]

Conclusions. The recent researches on superlubricity in our group have been reviewed. Several kinds of lubricants, including liquids and solids, have been found having superlubricity properties at macro- or micro-scale. These superlubricity phenomenon exhibited different dependences on sliding velocity, contact pressure and environment, due to diverse tribological mechanism. At present, there does not exist the uniformed mechanism for different kinds of superlubricity, nor a relationship between superlubricity at macro- or micro-scale. The application for superlubricity on the practical engineering is just the beginning. More efforts need to be carried out in the field of superlubricity.

Acknowledgment. The work is financially supported by NSFC (51527901, 51335005).

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MECHANICS AND SURFACE PHYSICS IN MICRO- AND NANOTRIBOLOGY

S. A. Chizhik

National Academy of Science of Belarus, Minsk, Belarus

Keywords: nanotribology; deformation; adhesion; surface energy; roughness and texture.

Nanotechnology has been formulated as a general multidisciplinary concept consisting of research at nanoscale and its practical applications for material science, mechanical engineering, and many other areas. The dimensional range in research and applications has shifted to micro/nano scale. High precision parts in precise mechanics (e.g., MEMS, magnetic recording devices, robotics, etc.) can be produced mainly with using the methods of nanotechnology.

Tribology as a science studying the contact of solids in their relative motion needs the adequate presentation of surface topography which appears due to action of natural structure as well as processing factors (type of surface manufacturing, inaccuracy of tools, etc.) [1]. Real surfaces, as a rule, contain at least two levels of asperities, such as waviness plus roughness or roughness plus subroughness. There is a great diversity of mathematical theories of roughness from simplest deterministic models (regular arrays of bodies with simple geometry) to complex models based on probability concepts and fractal geometry [2].

Analysis of the multiscale topography models has shown that the highest asperities are coming into contact and form the individual contact spots. Yet, the spots are produced by a set of smaller spots and their total area is much less than the real contact area. The strong interaction between the mating surfaces may occur within this area and contribution of physical and chemical factors to resistance for relative displacement of surfaces may be very significant. Application of computing power allows simulating rough contact based on 3D images of topography [3]. It is represented as a matrix of surface and may be generated by special algorithms or measured by scanning techniques.

Mechanical properties of contact materials should be taken into account at any scale level but depending on this level they can differ not only in magnitude but also in their physical interpretation. Scaling from macro to nanoscale can be related to transition from bulk properties of material to surface layer properties, local Young's modulus and nanoindentation data. Promising results are found in application of scanning probe methods to evaluation of mechanical properties. This application needs physical interpretation of experimental data and their self-affinity in changing the scale factor

In the framework of the two-level model, the multiply-connected pattern of real contact area was proved and the concept of physical contact area was developed that allows one to study redistribution of different physical forces during formation of real contact.

The real contact area was estimated with account for molecular surface forces. The features of the contact formation were revealed which depend on geometric parameters of rough surfaces, mechanical behavior of contacting materials, external load, and surface forces.

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"TRIBOLOGICAL HEALTH CARE" – THE AUSTRIAN MODEL OF AN EXCELLENCE CENTRE FOR TRIBOLOGY AND ITS ORIENTATION TOWARDS THE SPECIALIZED BASIC-ORIENTED INDUSTRIAL RESEARCH

F. Franek

AC²T research GmbH – Excellence Centre of Tribology, Wiener Neustadt, Austria, franek@ac2t.at

Keywords: porous bearings; laser claddings; additive degradation; MD simulation.

General situation. Tribology – similar to medical sciences – deals with complicated systems characterized by a lot of interactions of components and influencing parameters. From medical sciences we know measures or steps that can be seen as well in tribological research for and in close connection with industry: *diagnosis*, *therapy*, *pathology*, and *prophylaxis*. The Austrian Excellence Centre of Tribology (AC²T) offers relevant services in "tribological health care" as research provider to the industry – in Austria and international.

The institution. AC²T is a privately organized research institution (research GmbH), but superbly embedded into an Austrian governmental research funding program ("COMET", open for partners worldwide) provides a comprehensive laboratory infrastructure (complemented by other institutions on site, viz. Technology & Research Centre Wiener Neustadt) and a staff comprising about 140 persons educated in the mother disciplines of tribology.

Selected research topics. *Diagnosis:* Porous journal bearings are used in large quantities. Wear resistance of such bearings operated at high loads and small rotational speed is methodically investigated in relation to their friction behaviour (and ascertain the lubrication conditions), in such way leading to rankings of bearing–oil combinations according to various tribological properties. [1] – *Therapy:* In metal forming applications the tools suffer from high wear attack under high temperature conditions. Ni-based self-lubricating coatings containing Ag and MoS_2 prepared by means of laser cladding provide an improvement in terms of both friction and wear at high temperature [2]. The addition of MoS_2 enables achieving a uniform silver distribution within the resulting cladding by means of an encapsulation mechanism thus providing better lubrication and reducing wear susceptibility. – *Pathology:* Degradation of oils and additives are of major influence on the death of lubricated tribosystems especially in automotive applications. By the use of advanced analyses, e.g. mass spectrometry, the mechanisms of aging can be revealed. [3] – *Prophylaxis:* Modelling and simulation of tribological stresses and processes help to Analyses help to identify critical conditions and to derive targeted countermeasures as can, e.g., be demonstrated by MD simulation of a grinding process and its influences on a polycrystalline material, especially microstructural changes of grains, plastic deformation, twin formation, and rotation. [4]

Acknowledgements. Major parts of the research work resp. the examples reported here were supported financially by the Austrian COMET program, managed by the Austrian Research Funding Agency FFG (Project XTribology, no. 849109.

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MODELING OF THE RESIDUAL STRESSES EFFECT ON ACCUMULATION OF CONTACT FATIGUE DAMAGE IN ROLLING FRICTION

I.G. Goryacheva and E.V. Torskaya

Ishlinsky Institute for Problems in Mechanics, Moscow, Russia, goryache@ipmnet.ru

Keywords: residual stresses; contact fatigue; rolling contact.

Purpose of study. Modern methods of surface treatment of materials used in friction units (bearing elements, wheels, rails, etc.) are usually aimed at strengthening the surface layers of friction pair elements. In many cases, as a result of processing, a field of residual stresses is formed, which influences on the stress distribution in subsurface layers of materials in frictional interaction. In the framework of this study, the effect of residual stresses on the rate of accumulation of contact fatigue damage arising under cyclic loading of the surfaces of interacting bodies under rolling friction conditions is considered.

Contact problem formulation and the method of solution. A rolling contact of an elastic cylinder along the boundary of an elastic half-space of the same material is considered under the assumption that tensile or compressive residual stresses of constant magnitude act in an elastic half-space. The contact region consists of a slip subregion, in which the shear and normal stresses are related by the Coulomb – Amonton friction law, and the adhesion subregion, in which the velocities of the elastic displacements of the contacting bodies' surface points in the tangential direction are equal. Based on the solution of the contact problem, the distributions of normal and shear stresses at the boundary of the elastic half-space are determined, which are then used to calculate the internal stress in the elastic half-space taking into account the residual stresses. Under the assumption that the damage accumulation rate is a function of the amplitude values of the principal shear stresses arising in the surface layers of the material during the cyclic deformation the contact fatigue damage is calculated as the function of the number of cycles.

Result and discussion. Distributions of the principal shear stresses and their amplitude values are studied depending on the distance from the half-space surface. The influence of relative slippage, friction coefficient, and residual tensile stresses on the distribution of amplitude values of principal shear stresses is analyzed.

The model developed was used to analyze the influence of the residual stresses arising in the subsurface layers of the rail material during surface treatment on the rate of accumulation of contact fatigue damage in the rail head under wheel track in cyclic loading [1]. As the variable input parameters, the load on the wheel, the friction coefficient, and the longitudinal slippage were considered. The test results on contact fatigue for rail steel [2] was also used in calculations. The influence of the input parameters on the amplitude values of the principal shear stresses and on the rate of accumulation of contact fatigue damage at the rail head has been analyzed. Based on calculation results, the effect of residual stresses in the surface layers of the rails on the rate of accumulation of contact fatigue damage in the rail head has been studied.

Acknowledgements. The research was supported financially by the Russian Foundation for Basic Research and Russian Rail/Wheel Transport (grant no. 17-20-01147).

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GREEN TRIBOLOGY – DEMANDS, PROBLEMS, SOLUTIONS

J. Padgurskas[1], D. Volskis[2], and M. Rukanskis[3]

[1]Vytautas Magnus University, Kaunas, Lithuania, juozas.padgurskas@vdu.lt
[2]Vytautas Magnus University, Kaunas, Lithuania, dariusvolskis@gmail.com
[3]Vytautas Magnus University, Kaunas, Lithuania, rukanskis@gmail.com

Keywords: green tribology; biodegradable; biomimetic; sustainable; renewable.

Concept. Green tribology as a science and technology for "ecological balance and tribological aspects of environmental and biological effects" is application-oriented and embraces tribological environmental and biological aspects. This multidisciplinary area of science and technology is very important for the mechanics, materials, chemistry, live nature sciences and all modern industries. Green tribology plays an important role in ensuring that all industrial systems are environmentally friendly [1, 2].

Principles of green tribology: 1) Minimization of heat and energy dissipation; 2) Minimization of wear; 3) Reduction or complete elimination of lubrication and self-lubrication; 4) natural (e.g., vegetable oil-based) and 5) biodegradable lubrication; 6) Sustainable chemistry and green engineering principles; 7) Biomimetic approach; 8) Surface texturing; 9) Environmental implications of coatings and other methods of surface modification; 10) Design for degradation of surfaces; 11) Real-time monitoring, analysis, and control of tribological systems during their operation should be implemented to prevent the formation of hazardous substances; 12) sustainable energy applications.

Areas and directions of implementation. Using a biomimetic approach, biodegradable lubrication, spontaneous lubrication and other new techniques, as well as their application methods for sustainable engineering and energy production, will ensure a sustainable development strategy, one of the main objectives of which is to reduce environmental pollution and promote sustainable consumption and production. meet the environmental requirements for economic growth. [3]. Therefore, integration in these areas remains a key challenge for green tribology and defines future research trends. These are the main areas of tribology that have the greatest impact on environmental issues and are therefore of paramount importance: 1. Biomimetic and self-lubricating materials / surfaces; 2. Biodegradable and environmentally friendly lubricants; 3. Tribology of Renewable and / or Sustainable Energy Sources. Combining these three areas, rather than focusing on narrow issues, would be of value to industry, where accidental loss or leakage of lubricants during use gets directly into the environment. This is particularly important in the water, agriculture and forestry sectors. There are no other alternatives to overcome these problems by replacing the use of fossil organic materials with an increasing proportion of alternative bio-based lubricants and by developing the use of waste materials of biological origin.

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EVALUATION OF ELASTIC AND ADHESIVE PROPERTIES OF SOLIDS AND COATINGS BY DEPTH-SENSING INDENTATION

F.M. Borodich[1] and N.V. Perepelkin[2]

[1]School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK, BorodichFM@cardiff.ac.uk
[2]School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK, PerepelkinM@cardiff.ac.uk

Keywords: BG method; estimation of material properties; depth sensing indentation (DSI); adhesion.

The modern models of dry friction, e.g. the multilevel model developed by Borodich and Savencu [1], show that one needs to know the adhesive properties of the contacting pair in order to reflect the features of real interactions between the slider and the surface. Here we describe the methods for evaluation of the work of adhesion (w) between the slider and the surface using depth-sensing indentation (DSI) data obtained by a spherical indenter. If the indenter is made of the same material as the slider, the extracted value of w can be used in tribological models.

First, we discuss both the Borodich-Galanov (BG) [2] and the extended BG (eBG) [3, 4] methods. The methods implement the model-based approach in which the theoretical (expected) force-displacement relation during DSI (the model) is adjusted to best fit the experimental DSI data. The eBG method allows one to use force-displacement relations in which the indentation force P and the indenter displacement δ are parametric functions of the dimensionless contact radius $\bar{a}$:

$$\delta/\delta_c = f_1(\bar{a},\delta_c,P_c),\ P/P_c = f_2(\bar{a},\delta_c,P_c), \tag{1}$$

here P_c and δ_c are the scaling parameters of the problem. They are subject to adjustment during fitting the experimental data points. The eBG method allows to identify *simultaneously* both elastic and adhesive properties of the sample, e.g. a thin coating. The unknown material properties can be found as they are connected to P_c and δ_c via known formulae, which depend on the theory of adhesive contact used to construct (1). It is important to note that the relations (1) are used to describe adhesive contact behaviour of coatings in both analytical, e.g. [5], and numerical-analytical, e.g. [6], approaches. The eBG method can be implemented in either case.

We validate the methods using both numerical simulations and processing real experimental data in the framework of the JKR theory of adhesive contact. Numerical simulations are based on asymptotic models for thin [7] and thick [4] layers compared to radius of the contact region. Experimental validation is based on the DSI of both bulk solid and layers of different thicknesses made of polyvinyl siloxane elastomer.

Acknowledgements. Dr. Perepelkin acknowledges funding via the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 663830.

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FRICTION-INDUCED NOISE AND VIBRATION

V.P. Sergienko[1], S.N. Bukharov[1], S.S. Negmatov[2], T.U. Ulmasov[2], and N.S. Abed[2]

[1]V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, Belarus, sergienko_vp@mail.ru

[2]State Unitary Enterprise "Fan va Tarakkiyot" of Islam Karimov State Tashkent Technical University, Tashkent, Uzbekistan, s.s.negmatov@mail.ru

Keywords: friction; vibration; noise; composite materials.

The vibroacoustic characteristics of friction joints, first of all brakes and friction clutches of vehicles, are critical factors that define their competitiveness. Undesirable noise and vibrations related to dissipation and transfer of mechanical energy is a two-sided economic and technical problem. As a result of elevated noise and vibration levels, machines tend to lose their dependability and durability, along with quality. The problem of reducing noise and vibration in brake units is crucial for both tribology and mechanical engineering. While the papers on this topic are abundant in quantity, the design and experimental methods promoting comfort and competitiveness of above products by meeting the existing directives, norms and standards are lagging behind.

A promising direction in solving this problem is the development of friction materials, which contribute to the reduction of vibration and noise generated during sliding friction. The available scientific data show that such an approach already at the design stage allows the selection of materials of a friction pair and, thus, control the vibro-acoustic characteristics of the friction devices. It is generally assumed that frictional self-oscillations, which are one of the causes of inhibitory noise and vibration, are due to the negative gradient of the friction coefficient with respect to sliding speed (i.e., the friction coefficient increases with decreasing sliding velocity) and its dependence on fixed contact time. Nevertheless, theories explaining the excitation of friction self-oscillations by processes occurring during stick (relative stop) and slip of friction elements, taking into account the corresponding static and kinetic friction characteristics, do not allow us to determine practical criteria for evaluating friction materials in point of the tendency to vibro-acoustic activity. The kinetic and static characteristics of a friction pair depend on load-speed conditions, the properties of friction materials and other factors. The results of a number of theoretical and experimental studies show that frictional self-oscillations are possible even under the condition of an ideal constancy of the friction coefficient.

This paper discusses approaches to optimizing the structure and composition of polymer composite friction materials (PCFM), which provide a reduction of friction-induced vibration and noise of brake systems and transmissions of machines. The dependences of the dynamic mechanical characteristics of PCFM on the type of polymer matrix, the plasticizers used for the matrix phase, differing in their composition and structure, have been experimentally studied. Noise and vibration tests of the developed materials in friction units, which allow simulate operation conditions of brakes and transmissions, confirmed the possibility of effectively reducing vibration and noise by increasing the damping ability of PCFM.

THE PROBLEMS OF OBTAINING BIODEGRADABLE GREASES

O. P. Parenago

A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences, Moscow, Russia

At present, in addition to the technical characteristics of modern lubricants that ensure reliable operation of all friction units, considerable attention is paid to the environmental aspects of their production, use and disposal [1, 2]. In this regard, the problem of obtaining biodegradable greases is becoming increasingly important, which is becoming the most urgent in the Northern and Arctic regions of Russia.

Currently, five main groups of chemicals are considered as base oils in the production of biodegradable lubricants [3]: high-unsaturated vegetable oils, low-viscosity polyalphaolefins, polyalkylene glycols, dibasic acid esters and poly-alcohol esters.

It is well known that biodegradability (table) vegetable oils and synthetic esters have a great advantage over mineral oils.

Table. **Biodegradability of base oils**

Base oils	Biodegradability, %
Mineral oil	20–40
Vegetable oils	90–98
Synthetic esters	65–100

The report presents the results of the development of biodegradable and low-temperature greases, promising for use in the Arctic and the Far North. As base oils was selected synthetic esters of dibasic acids (DOS) and esters of trimethylolpropane and pentaerythritol alcohol with a melting point of –50 to –60 °C. In addition, polyalphaolefin oils with different viscosity, also having a low pour point, were used. Thickeners lubricants served organic compounds, with potentially high ability for biodegradation: dicarbamids, as well as cellulose and its derivatives. In the case of dicarbamids, their synthesis was carried out in situ in the medium of the base oil by the interaction of toluene diisocyanate, aniline and aliphatic amine, as which primary amines with the number of carbon atoms 8, 12 and 16 were used. The content of the thickener in the oil varied in the range of 10–25 wt.%.

In the course of the work, the basic physical and chemical properties of lubricants were determined: colloidal stability, dropping temperature and tensile strength. In addition, the rheology of greases and their anti-wear activity were studied.

As a result of comparison of physical and chemical properties of greases based on esters of different structures and dicarbamamochevin as a thickener, it is shown that all indicators increase with the increase in the amount of thickener. It is also found that the above parameters for the same basic bases are generally higher when using cellulose derivatives as organic thickeners.

The figure shows typical flow curves of lubricants based on different basic principles and dicarbamids thickener.

An important characteristic is the effective viscosity determined at low temperature. It was shown that it at a shear rate of 10 s^{-1} and a temperature of –50 °C is about 500–900 Pa·s, which meets the necessary requirements.

The anti-wear activity index (wear spot diameter) in almost all cases is less than 0.6 mm.

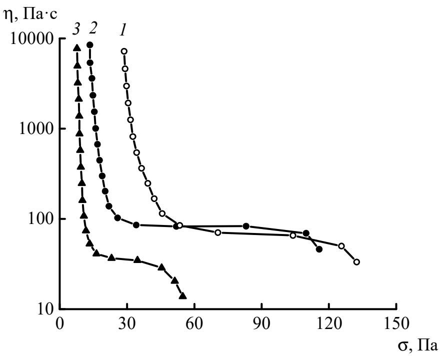

Figure. Flow curves of lubricants at 25 °C based on DOS (1), NB-5750 (2) and NB-7300 (3) containing 10% of the mass of the dodecylamine-based thickener

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EFFECT OF LASER SURFACE TEXTURING ON BOUNDARY LUBRICATION

Y. Meng[1] and L. Bai[1,2]

[1]State Key Laboratory of Tribology, Tsinghua Univ., Beijing, China, mengyg@tsinghua.edu.cn
[2]Qingdao Technological University, Qingdao, China, skdbailinqing@163.com

Keywords: laser surface texturing; boundary lubrication; tribo-chemistry.

Purpose. Laser surface texturing has been proved to be effective for enhancing tribological performance of many mechanical components [1]. In boundary lubrication, surface textures play an important role in terms of oil storage and supply to the contacting region. In addition, textures may affect the tribo-chemical reaction between lubricant additives and the substrate [2, 3]. However, synergistic effects of surface textures and oil additives have not yet been fully understood, which limits the application of surface texturing in boundary lubrication conditions. The purpose of this work is to provide some insights into the mechanism of synergistic effects of laser surface texturing and ZDDP/MoDDP additives on boundary lubrication.

Method. Tribological experiments were performed on a reciprocating tribometer UMT-3 by using a ball-on-plate module as shown in Fig. 1. Base oil (GTL, gas to liquid) with and without the oil additives of ZDDP and MoDDP were used as the lubricating oils. The friction coefficient and lifespan of texture-free surface, circular dimple surface and line grooves surface were tested and compared under flooded and starved boundary lubrication conditions.

Results and discussion. Friction tests of surface textures subject to boundary lubrication were performed in this study. The following conclusions can be drawn from the test results. (1) Under flooded boundary lubricant condition, the friction coefficient was more responsive to texture parameters when oil additive was contained in the lubricant than only base oil was used. Meanwhile, the optimization parameters of circular-dimple and groove textures with oil additive were different from those for the base oil. (2) Appropriate design of surface texture can promote the formation of tribofilms, which contributes notably to improve the friction and wear properties subject to the boundary lubrication conditions. (3) The synergistic effects of surface textures and oil additives ZDDP and MoDDP significantly extended the effective lubrication time as compared to individual effect under starved lubrication conditions (Fig. 2).

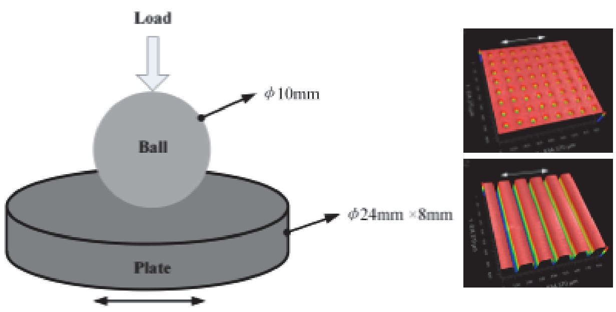

Fig. 1. Schematic of test rig

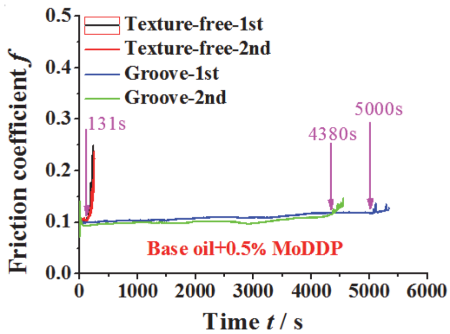

Fig. 2. Effective lubrication time (groove)

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TRIBOLOGICAL PROPERTIES AT CONTACT INTERACTION OF NANOSTRUCTURE COATINGS

A.Kh. Janahmadov

Azerbaijan National Aviation Academy, Baku, Azerbaijan, e-mail: ajanahmadov@gmail.com

Keywords: tribological properties; contact interaction; nanostructure coatings; transition criteria of the contact mode; substrate; hardness; elasticity; near-surface layer.

Surface engineering of nanostructured coatings is one of the most promising and fast developing fields of the modern materials science [1]. Nanostructured surfaces are already widely used in many areas, such as construction and environmental protection; military and defense equipment (to protect against corrosion and wear); energy, aerospace and automotive sectors.

One of the main properties of nanostructured coatings is an improved hardness. According to the classical theory of tribology, this particular property of nanostructured coatings is of special importance in the tribological applications. However, numerous studies of contact friction show that, along with the high hardness, it is equally important to achieve appropriate levels of elasticity. This leads to a necessity to introduce the concept of optimization of both hardness (H) – to its (sufficiently) high level; and modulus of elasticity (E), when we deal with tribological coatings [2–4].

From our prospective, the tribological phenomena, observed during the contact interaction, and the resulting changes in the coating parameters should be subject to the rules of mesomechanics of the contacting surface layer. The loaded solid objects are considered as multilevel self-organizing systems, in which macro-, meso-, and meso-levels are organically interconnected. Taking into account this phenomenon, we developed a general scheme for the tribological phenomena of the contact interaction, and for the observed resulting changes in the coating parameters.

For the coating surface, the ratio of hardness to modulus of elasticity is very important, we call it the criterion of transients $J_k = H/E$, since the coating must under changes in complete agreement with substrates, when the system deforms under load. This is done by minimizing both the maximum pressure on the surface of contact with the hard coating, and the stress difference at the interface between substrate and coating. Moreover, such a dimensionless criterion ensures a uniform impact of parameters on the friction process (the contact interaction), which allows to qualitatively evaluate the performance characteristics of tribocontact.

The ratio H^2/E is equally important, it defines the elastic resilience, i.e. the ability to form an energy absorbed by strain. This relation is the best parameter for ranking the triboeffect of various materials. By using the measured hardness (H) and material elasticity (E), we can describe other surface properties of material that are important for the tribological applications, such as the pressure, generated by the thermomechanical contact, and the stiffness of cracks. In each case, the different coating characteristics maybe required to maintain a balance between elasticity and stiffness, viscosity and hardness, frictional and tribological behaviors.

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TUNING THE WEAR PROPERTY OF GRAPHENE VIA IN SITU SUBSTRATE OXIDATION

Ming Ma[1] and Shuji Zhao[2]

[1]Tsinghua University, Beijing, China, maming16@tsinghua.edu.cn
[2]Tsinghua University, Beijing, China, zhao-sj16@mails.tsinghua.edu.cn

Keywords: graphene; AFM; wear; oxidation; Raman spectra.

Purpose. While there has been a large amount of studies about wear resistance of graphene layer [1–5], there is no study about the effect of oxidation between graphene and substrates on anti-wear properties of graphene. Thus, it is necessary to explore the relationship.

Method. Single layer graphene was grown by traditional chemical vapor deposition (CVD) method [6]. After exposing the specimen to atmosphere for six months, the tribological characteristics of graphene were examined by AFM under ambient conditions. Raman microscopy was used to characterize the thickness of graphene under ambient condition.

Result and discussion. The red region in fig. 1a corresponds to copper with high oxidation degree (HOD), and white region corresponds to low oxidation degree (LOD) copper [7, 8]. Raman results were shown in fig. 1b. In both cases, the Raman spectrum of graphene had no *D* peak, and the ratio of the intensity of *G* peak to *2D* peak was around 1/2, indicating that the graphene on both substrates was of single layer and intact.

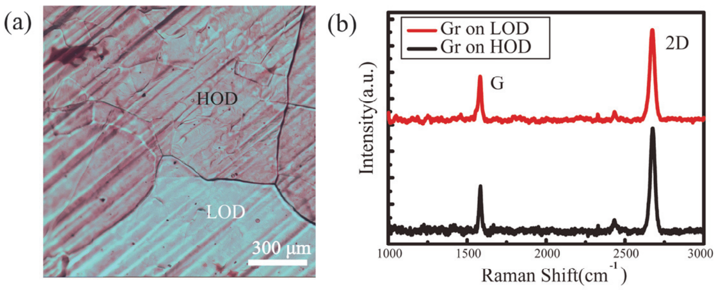

Fig. 1. (a) Optical image of the substrates. (b) The Raman spectra of the graphene layers on substrates

The wear tests were carried out by scratching the graphene layer. The normal force was increased at 0.148 μN intervals, the results were shown in fig. 2a (LOD) and fig. 2b (HOD).

Large friction indicates graphene layer was worn. From fig. 2a and 2b, it is evident that once the graphene layer got worn, the wear rate of graphene on HOD substrate was much higher. The test of the upper limit of the wear resistance of graphene done on the intact region (blue rectangle in fig. 2a) as shown in fig. 2c. As shown in fig. 2a, the worn area for graphene layer on LOD substrates gradually extended along the damaged line, while on HOD substrates the graphene layer was peeled along the damaged line in a form of large sheets (fig. 2b).

The regions after wear tests were also characterized by Raman spectroscopy. Fig. 3a shows the optical image of the worn area on the LOD substrate. For those regions still remain low friction (point 1), the presence of D and G peaks (fig. 3b) indicate that the graphene layer still remained with defects. For point 2 which corresponds to the high friction region in fig. 2c, the absence of G peak shows that the graphene layer was completed destroyed. For graphene layer on HOD substrate, fig. 3b shows the optical image after the wear tests were performed. The Raman spectroscope measured within the wear region shows no D and G peaks (point 3), indicating the absence of graphene layer after wear test. However, there were D, G, 2D peaks appeared at the wear boundary (point 4), and the intensity of G peak is much larger than that of 2D peak. This indicates that during the wear test, the graphene layer was pushed to the edge of the wear region and piled up.

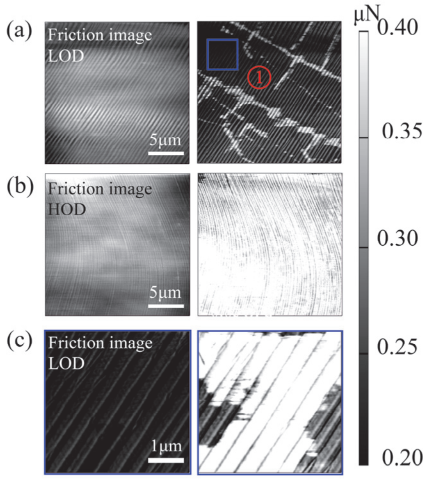

Fig. 2. Friction force images at the same location on (a) LOD and (b) HOD substrates, the normal force was 0.148 μN and 1.48 μN respectively. (c) Friction force images measured within the blue square area in fig. 2a, the normal force was 1.776 μN and 3.108 μN respectively

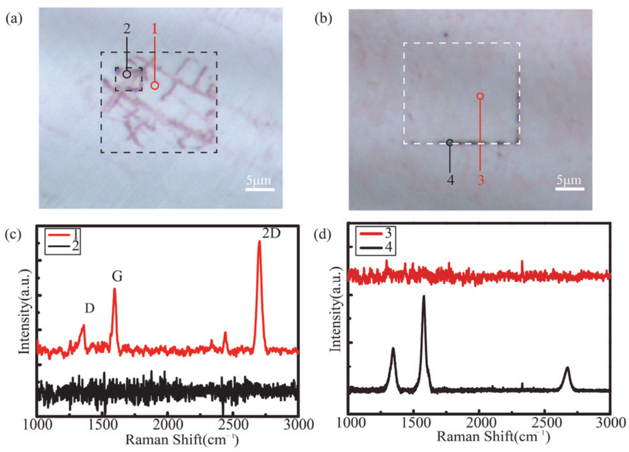

Fig. 3. Optical images of the worn area, a for LOD and b for HOD. Raman spectra obtained in a (c) and b (d)

Our experiments showed that the inner region of graphene exhibited better anti-wear property on low oxidation degree substrates than high oxidation degree substrates. The damage of graphene on LOD substrate developed slowly along the damaged line, while on HOD substrate it expanded rapidly in the form of large sheets.

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EFFECT OF RELAXATION AND DISSIPATIVE PROCESSES ON DYNAMIC STRAIN AND WEAR RESISTANCE OF TRIBOSYSTEMS

V. Shevelya[1], G. Kalda[1,2], W. Orlowicz[2], and A. Trytek[2]

[1]Chmelnickiy National University, Chmelnickiy, Ukraine, valeriy.shevelya@gmail.com
[2]Rzeszow University of Technology, Rzeszow, Poland, kaldagal@prz.edu.pl

Keywords: rheology; relaxation; tempering; dissipation; internal friction.

Effect of the tempering temperature of hardened carbon steel and conformable structural changes on physical-mechanical properties and tribological characteristics during dry sliding friction was researched. It is shown, that relation between adhesive and deformational components of the frictional force depends on acquired during tempering viscoelastic properties that influence on mechanism of the contact interaction and dissipative processes. Viscoelastic properties are detected by two basic rheological parameters: modulus of elasticity and damping capacity, with which the viscoelastic coefficient is connected. The theoretical analysis of dissipative properties of the viscoelastic frictional contact dissected subject to the structure of tempered steel on the base of examined standard rheological models. Effective mechanisms of decreasing of the dynamical tensity and increasing of the wear resistance of the frictional contact were examined.

Temperature dependences of descriptions of internal and external friction of the thermo treated steel were probed. It is rotined that force of external friction is closely related to the internal friction the mechanisms of which depend on amplitude and speed of deformation of spots of actual contact and from a temperature and structural state of materials. An internal friction is the basic mechanism of dissipation of mechanical energy with transformation of it to the warmth both at deformation and at adhesion co-operation of surfaces of friction. The temperature intervals of development of tribodynamic deformation senescence are set with the sub structural work-hardening and friction self-excited oscillations.

The effect of external dry friction of carbon steel on sub structural changes, which control dynamic-stress relaxation processes, which determine the dissipation properties of frictional contact, has been studied by the method of amplitude-dependent internal friction. The research results show that the dissipation ability (energy content) and wear resistance of steel can be increased by the realization of dynamic mechanisms of stress relaxation directly during friction.

The surface strengthening of metals by electric-arc plasma shows new possibilities for control of the properties of materials during their thermal treatment. The influence of indicated surface treatment of cast iron and steel on their mechanical and rheological properties in connection with wear resistance are studied. It is shown, that acoustic emission activity as indicator of relaxation ability on certain conditions of scratch-testing forms maximums. Mechanisms of acoustic emission changing and indicator of elastic aftereffect of steel in comparison with steel after thermal strengthening are discussed.

The changing of sclerometric parameters and acoustic emission activity of friction zones depending on tempering temperature of carbon steel quenching under conditions of cyclic-reverse scratch-testing was studied. The tribological analogue of Baushinger effect, which occurrence depends on the structure of steel tempering was experimentally researched. Physical nature of Baushinger's triboeffect as rheological parameter of relaxation and dissipative properties of frictional contact was examined in connection with acoustic emission activity and amplitude dependent internal friction of steel.

SELF-LUBRICATING POLYMER COMPOSITES WITH CORE-SHELL STRUCTURED NANOSPHERES

Guoxin Xie, Lin Zhang, Dan Guo, and Jianbin Luo

State Key Laboratory of Tribology, Department of Mechanical Engineering,
Tsinghua University, Beijing 100084, China
email of corresponding author: xgx2014@tsinghua.edu.cn (Guoxin XIE)

Keywords: self-lubricating composites; core-shell nanoparticles; low friction and wear; high compressive strength.

Core-shell nanoparticles play an important role in improving the mechanical properties of engineering materials. However, there have been few reports on the lubrication properties of polymer composites reinforced with core-shell nanoparticles. It may be an efficient way to enhance the lubrication properties of polymer composites by constructing core-shell nano-fillers, presumably as a consequence of the enhanced adhesion at the matrix-filler interface as well as the better dispersion of the filler in the composites. Moreover, to coordinate a polyer composite with remarkable mechanical properties and outstanding lubrication properties is important for its practical applications. In the present work, core-shell nanoparticles have been as the basic element as the continuous matrix in polymer composites for improving both the mechanical and lubrication properties. Specifically, synthesized core-shell nanospheres with polytetrafluoroethylene (PTFE) as the core and polymethyl methacrylate (PMMA) as the shell have been adopted as the structural units to form bulk nanocomposites. The characterization results suggest that as compared with pure PTFE, the compressive strength of the PTFE@PMMA nanocomposite obviously increase up to one order of magnitude, the lowest friction coefficient can be reduced to as low as 0.03, and the wear rate decreases up to two orders of magnitude. The mechanical and lubrication properties of nanocomposite could be adjusted by changing the core-shell ratio. In the talk, the underlying mechanism of the strengthening effect of the core-shell structure nanospheres as the basic element will be discussed. Moreover, the structural evolution of the different phases in the composite under different temperatures will be shown.

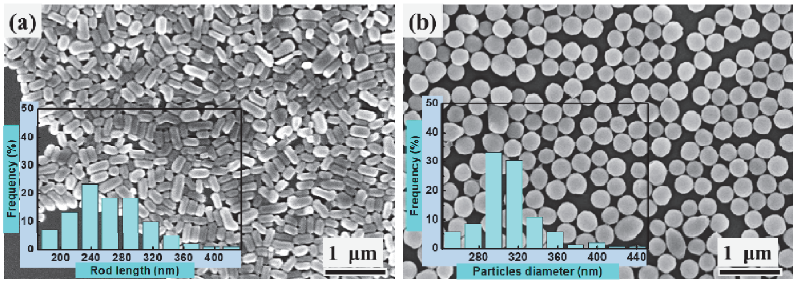

Figure. SEM micrographs of the PTFE latices (a) and PTFE@PMMA (1.5)

Acknowledgements. This work was supported by the National Natural Science Foundation of China (Grant No. 51822505, 51475256) and Beijing Natural Science Foundation of China (Grant No. 3182010).

STUDY OF THE INFLUENCE OF NANOADDITIVES IN METAL-CERAMIC MATERIALS ON FRICTION AND WEAR PROCESSES

A.Ph. Ilyushchanka, M.A. Andreev, and A.V. Leshok

O.V. Roman Powder Metallurgy Institute, Minsk, Belarus. E-mail: Alexil@mail.belpak.by

Keywords: friction; wear; tests; coating; friction material.

Text. The paper presents the study results of the influence pattern of nanoscale additives on the properties of the formed metal-ceramic materials, including coatings, as well as the study of friction and wear processes.

A composite coating based on metals with the addition of ultradispersed diamonds (UDD), formed by the method of ion-beam sputtering of a composite target, makes it possible to ensure the cutting tool life. The composite target may consist, for example, of pressed chromium powder with the addition of UDD ultradispersed powder in the amount of up to 5 wt.% with a particle size of 1–5 nm. The addition of UDD powder to a chromium sputtering target increases the number of nucleation centers during formation. The presence of nanoscale UDD powder particles in the sputtering target increases the number of nucleuses during the entire crystallization process and leads to an increase in the number of individual crystals in the coating. In this case, a smaller grain is formed. Nanoscale particles of UDD powder are located along the grain boundaries, serving as a place of concentration of dislocations, and prevent them from "creeping" into neighboring grains under loads and high temperatures in aggressive environment, thereby increasing the corrosion-resistant and mechanical properties of coatings [1, 2].

The use of nanodispersed aluminide powders in the composition of a sintered friction material based on copper, designed to work under conditions of boundary friction, has increased the efficiency of the material run-in by reducing the formation time of the determined value of the friction coefficient. It was found that the optimal value of nanodispersed aluminide additives should be 1.3–1.8 wt.%. This enabled to keep the mechanical strength of the material, as well as to increase the friction coefficient value of the base friction material MK-5 from 0.03–0.04 up to 0.04–0.05. Moreover, their use contributes to reducing the wear of both the material itself and the counterbody.

In the process of conducting thermal-physical tests of friction material, it was found that aluminides can increase the thermal conductivity of the material from 34 to 41 W/(m·K), increasing the slipping time of a friction pair [3].

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STUDY ON THE TRIBOLOGICAL PROPERTIES OF 40CrNi STEEL AFTER PLASMA SURFACE HARDENING

Zh.B. Sagdoldina, B.K. Rakhadiov, Z.A. Satbaeva, and D.R. Baizhan

S. Amanzholov East Kazakhstan State University, Ust-Kamenogorsk, Kazakhstan, Sagdoldina@mail.ru

Keywords: surface plasma hardening; wear resistance; microhardness; tribology.

Surface thermal hardening of steel parts is one of the most effective and efficient ways to increase the service life of loaded elements of machines and mechanisms. In this case, only the most loaded working surface of the part is strengthened, leaving the core intact. At the same time, the progress in improving the quality of heat treatment of the working surfaces of parts is associated with the use of concentrated energy sources: electron and laser beams, plasma jets [1, 2]. At the same time, of all the existing methods of hardening in terms of their technical and economic indicators and the results of a comparative analysis, plasma surface hardening is recommended. In this work is the use of surface plasma quenching technology, providing a given structure of the surface layer to increase the hardness, wear resistance, and strength characteristics of 40CrNi steel.

For surface plasma quenching of steels was used electrolyte containing up to 15% sodium carbonate and 15% urea. Plasma surface hardening (PSH) is carried out by exposure to electrolytic plasma for 3 seconds, followed by cooling in a flow-through electrolyte. The microhardnesses of steel samples were measured on the device PMT-3 with the load on the indenter P = 1 N and the dwell time at this load of 10 s. Tribological sliding friction tests were carried out on a THT-S-BE-0000 tribometer. Abrasive wear samples were tested on the experimental setup for testing abrasive wear when rubbing with not rigidly fixed abrasive particles according to the “rotating roller - flat surface” scheme.

The microstructure of the cross-section of 40CrNi steel after PSH is shows that the cross-sectional structure of the steel is conventionally divided into 3 zones. The hardened layer is a homogeneous fine-grained martensitic structure. As the depth increases, a non-uniform structure is formed in the heat-affected zone, which is martensite and perlite. Then, this zone moves to the pearlite-ferritic structure, i.e. to the structure of the matrix. The thickness of the modified layer is 1–1.2 mm.

On the basis of the obtained research results, it can be said that, after PSH the mechanical and tribological properties of the steels increase. After the PSH with a heating time of 3 min, the microhardness of steels 40CrNi. The wear rates for samples of steels 40CrNi a significant decrease in wear rate in comparison with the initial one from 8.9 $mm^3/(N \cdot m)$ to 0.3 $mm^3/(N \cdot m)$, which indicates a significant increase in the wear resistance of the steels.

Thus, the main advantage of the PSH is the possibility of obtaining a modified martensite layer with carbide particles on the surface of the steel. In this case, the viscous core of the material does not change, which consists of a ferritic-pearlitic structure. The formation of a modified layer of fine-grained martensite with carbide particles in the surface layers will positively affect the performance properties of the parts.

The research was performed within the grant financing of scientific research for 2018–2020 of Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan (Grant BR05236748).

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TRIBOCHEMICAL ASPECTS OF WEAR OF AMORPHOUS SILICON DIOXIDE-PTFE NANOCOMPOSITES

V.N. Aderikha[1] and V.P. Novikov[2]

[1]V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus (NASB), Gomel, Belarus, vnad@tut.by,
[2]Scientific-Practical Materials Research Centre of NASB, Minsk, Belarus

Keywords: nanocomposite; wear; tribochemical processes; polytetrafluoroethylene; silicon dioxide.

Filling of PTFE with small quantities (1–5 wt.%) of nanosized oxides, carbides, nitrides of metals, carbon allotropes (carbon black, nanotubes, expanded graphite), etc. allows to reduce the wear rate by 2…4 orders of magnitude compared to the neat PTFE to the level of $10^{-6} – 10^{-8}$ mm^3/(N·m). The wear rate of the low-filled PTFE-based nanocomposites is known to greatly depend on the relative humidity of the ambient atmosphere (up to 2 orders of magnitude [1, 2]), and the composition of the counterface metal [3], which indicates significant role of the tribochemical processes in the wear process.

The study aims to investigate the processes evolving in the friction layer of the low-filled amorphous silicon dioxide (SiO_2)-PTFE nanocomposites in dry friction on chromium steel grade 40X and stainless steel 40X13 under ambient conditions in comparison with similar nanocomposites based on adhesion-activated PTFE (PTFE-A).

Objects and Methods – nanocomposites based on PTFE and PTFE-A, prepared by treating PTFE powder with sodium solution in liquid ammonia, filled with 2 wt.% of SiO_2 (grade BS2, surface area 100 m^2/g). The friction surfaces of the composites were examined by ATR FTIR, EDAX, SEM.

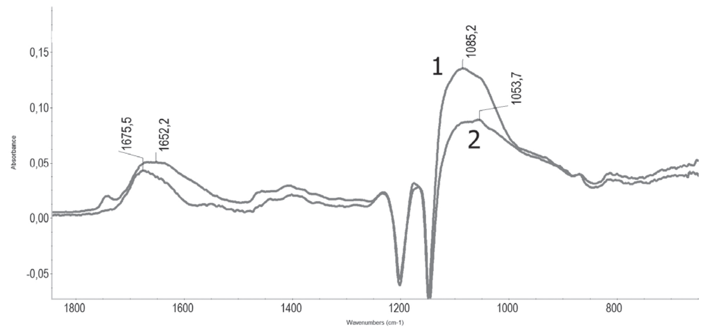

Figure. ATR FTIR subtraction spectra of the friction surfaces of PTFE/SiO_2 (1) and PTFE-A/SiO_2 (2) nanocomposites after friction on 40X steel

Results and Conclusion. It is found, that the wear rates of the two nanocomposites on the chromium steel 40X are similar and amount to ~ $1·10^{-6}$ mm^3/(N·m). At friction on the stainless steel 40X13, the wear rate of PTFE-A/SiO_2 nanocomposite remains almost unchanged, while that of PTFE/SiO_2 increases by a factor of 30, which points to a significant role played by Fe_2O_3 in providing for its low wear. IR spectroscopic analysis of the friction surfaces reveals formation of –Si–O–C– chemical bonds in both composites, however, the process is more prominent in the composite based on the functionalized PTFE-A, reflected by splitting of the –Si–O– absorption band at ≈ 1085 cm^{-1} with a –C–O– band at ≈ 1054 cm^{-1} (figure). This signifies evolution of chemical bonding between the matrix and the filler, which reinforces the friction layer and reduces the rate of wear on corrosion-active steel. The degree of the filler bonding, less expressed in the case of PTFE/SiO_2 nanocomposite, influences the rate of filler accumulation in the friction layer, which presumably plays only a secondary role in reducing the composite's wear rate.

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EFFECT OF NATURE OF ALLOYING ELEMENTS ON TRIBOTECHNICAL PROPERTIES OF COMPOSITE CARBON COATINGS

A.V. Rogachev[1], A.S. Rudenkov[1], D.G. Piliptsov[1], and Xiaohong Jiang[2]

International Chinese-Belarusian scientific laboratory by vacuum-plasma technologies
[1]F. Scorina Gomel State University, Gomel, Belarus, rudenkov@gsu.by
[2]Nanjing University of Science and Technology, Nanjing, China

Keywords: alloy; metal; carbon; tribotechnical properties.

Doped carbon coatings are complex heterophase objects, the tribological properties of which are determined by the choice of methods and formation modes, the sp^2/sp^3 ratio of hybridized atoms, the nature and concentration of alloying elements [1–2]. In this regard, a scientifically based selection of individual components of the coating, the study of chemical interaction processes at the deposition stage, interfacial processes in the carbon matrix volume is an urgent task, the solution of which will allow the development of basic technological methods for creating thin-film systems with adjustable functional. The aim of the work was to study the influence of the modes and conditions of doping, the nature of the alloying elements of various chemical activities (Ti, Cr, Al, Cu) on the tribological properties of composite carbon coatings.

Experimental samples were formed using two methods of doping, characterized by different contents of the droplet phase: electric arc evaporation and magnetron sputtering of metals. The generation of carbon plasma flows, in both cases, was carried out using a pulsed cathode-arc source.

It is shown that doping of carbon coatings by the method of electric arc evaporation of metals, as compared to doping with magnetron, is characterized by a higher content of the droplet phase, and therefore contributes to greater abrasive wear of the surface of the counterbody when working in a friction pair with such coatings. However, if we abstract from the quantitative differences of the tribological characteristics caused by the droplet phase, in terms of the choice of the alloying element, its concentration, there are a number of common trends for both methods. It was found that, regardless of the doping method, the friction coefficient of composite carbon coatings increases with increasing concentration of the alloying metal. In both experiments, the lowest coefficient of friction, with relatively equal concentrations of the alloying element, are characterized by coatings containing copper, which plays the role of a solid lubricant and provides the lowest coefficient of friction. Greater wear resistance, regardless of the method of doping, characterizes coatings containing carbide-forming elements (Ti, Cr). In the interaction of the counterbody with such coatings, solid inclusions of metal carbides contribute to its wear, in the case of electric arc doping, more rapid due to the presence of the droplet phase.

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FEATURES OF FRICTION OF GRADIENT TITANIUM CARBON COATINGS

A.V. Rogachev[1], Bing Zhou[2], D.G. Piliptsou[1], A.S. Rudenkov[1], and E.A. Kulesh[1]

[1]F. Scorina Gomel State University, Gomel, Belarus, pdg_@mail.ru
[2]Taiyuan University of Technology, Taiyuan, China

Keywords: gradient film; metal; carbon; tribotechnical properties.

One of the areas of modern materials science is the development of coatings operating at high temperatures and variable loads. Consistently high-performance properties of the surface of the hardened parts and tools are achieved at a certain ratio of the hardness of the substrate and coating. When the tool surface is hardened using α-C coatings, there is a sharp transition from a relatively soft tool base to a high-hard coating with the formation of a sharp boundary in the distribution of mechanical properties, which leads to an increase in internal stresses, and, consequently, the activation of the coating destruction process by contact pressure during friction [1]. To reduce abrupt changes in the structure, gradient metal-carbon coatings are deposited on the surface of the tool, allowing to smoothly change the mechanical properties of the layer thickness, which leads to a decrease in the effects caused by a sharp jump in mechanical properties [2]. The kinetic friction curves of gradient coatings depend on their architecture and chemical composition, and show differences in the initial stages of friction. For Ti/α-C(5...20 Hz):Ti coating is characterized by a minimum burnishing time, which is determined by the low roughness, as well as the presence in the upper layer of titanium and titanium oxide, which determine the reduction of the setting energy at the initial moments of friction by reducing the surface energy (typical for titanium oxide), as well as high plasticity gradient coating. The presence of a drop phase of titanium in the upper layer leads to a decrease in the wear resistance of the counterbody and an increase in the friction coefficient μ. Coefficient of friction and wear for Ti/α-C (5...20 Hz):Ti:N_2/α-C:N_2 is significantly lower than that of nitrogen-unalloyed coatings containing titanium. It is shown [3] that the presence of nitrogen atoms in the structure of Ti/α-C (5...20 Hz):Ti:N_2/α-C:N_2 coating determines a decrease in the concentration of carbon bonds in the state of sp^3 hybridization and an increase in the degree of orientation with a decrease in the size of Csp^2 clusters, which leads to an increase in microhardness. On the other hand, a lower coefficient of friction Ti/α-C (5...20 Hz):Ti:N_2/α-C:N_2 can be further explained by the formation of graphite in the surface layer of the covering [3].

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ANALYSIS ON FRICTION AND WEAR OF TUNGSTEN NICKEL IRON BALL AND 316 STEEL IN ADS BALL FLOW TARGET

Xuanyu Sheng[1], Lanwen Wang[2], and Wenjie Liu[3]

[1]Department of Mechanical Engineering, Tsinghua University, Beijing, China
[2]Department of Mechanical, Electrical and Information Engineering, Shandong University (Weihai), Shandong, China, 13176803577@163.com
[3]Department of Mechanical Engineering, Tsinghua University, Beijing, China

Keywords: ADS; ball flow target; tungsten-nickel-iron alloy; 316 stainless steel.

Abstract. The accelerator-driven subcritical system is a technique for bombarding a target with a beam of high-energy protons, producing neutrons from a hashed target, and providing it to external subcritical reactors to maintain its chain reaction as a technique to receive high-energy proton beam bombardment, and the neutron-generating target is the core part. This paper discusses the working conditions of the new target ball flow target in the ADS, and the friction and wear conditions of the tungsten nickel iron ball pin and 316 stainless steel under different conditions. Research shows that the wear of tungsten-nickel iron ball pin is much smaller than the wear of 316 stainless steel. When the 3mm diameter tungsten-nickel iron ball pin rubs against 316 stainless steel at different temperatures, the friction coefficient basically increases with the increase of temperature. Due to the influence of the surface oxide layer, the higher the temperature, the more severe the oxidation and the greater the fluctuation of the curve. When the tungsten-nickel iron ball pins of different diameters are rubbed with 316 stainless steel at normal temperature, the friction coefficient basically increases with the decrease of the radius.

TRIBOLOGICAL PROPERTIES OF PTFE-BASED COMPOSITES REINFORCED WITH COMPLEX FILLERS

A.A. Okhlopkova[1], T.S. Struchkova[1], A.P. Vasilev[1], S.A. Sleptsova[1], and P.N. Grakovich[2]

[1]North-Eastern Federal University, Yakutsk, Russia, e-mail of corresponding author: gtvap@mail.ru
[2]V.A. Belyi Metal-Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, Belarus

Keywords: polytetrafluoroethylene; carbon fibers; layered silicates; wear; friction.

Polytetrafluoroethylene (PTFE) and polymer composite materials (PCMs) based on it are widely used in engineering application [1–3]. To improve the tribological properties of PTFE using different type fillers – carbon fiber (CF), alumina, layered silicates and nanoparticles [2–4]. In spite of the fact, few studies have been devoted to studying the effect of combining carbon fibers together with layered silicates on the properties and structure of PTFE. Thus, the influence of combined fillers (CF/vermiculite/ultrafine PTFE (UPTFE) and CF/kaolin/UPTFE) on the properties and structure of PTFE was investigated.

In figure shows the results of study of the wear-resistance of PTFE and PCM and micrographs of worn surface by electron microscopy. It is seen that the additional introduction of layered silicates and UPTFE in PTFE/CF leads an increase in wear resistance by 3–3.5 times. The SEM micrographs on of worn surfaces of the composites with combined fillers shows the formation of secondary structure. Thus, it was CF and layered silicates together with UPTFE protect the polymer layer of PCMs between individual fibers on the surface friction. This leads to a minimal destruction of individual fibers during frictional contact.

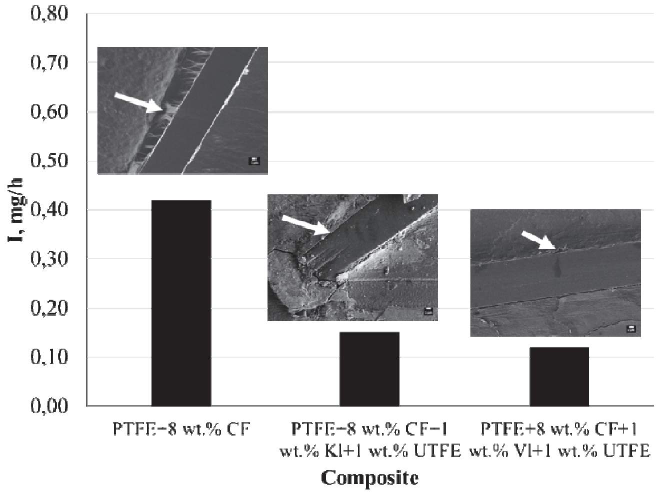

Figure. Results of wear rate and worn surface of PTFE and PCMs

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TRIBOCHEMICAL REACTIONS ON THE FRICTION SURFACE OF PTFE COMPOSITES

S. Sleptsova and A. Okhlopkova

Ammosov North-Eastern Federal University, Yakutsk, Russia, okhlopkova@yandex.ru

Keywords: polytetrafluoroethylene; layered silicate; IR-spectroscopy; tribochemistry.

Tribochemical reactions of polymers and polymer composites that occur during the friction play a significant role in developing methods for enhancing their wear resistance and understanding mechanisms of friction. The use of IR spectroscopy and X-ray photoelectron spectroscopy to study structural transformations that occur during the friction of the polymer composite materials with various fillers has revealed the formation of intermediate products in the course of the oxidative destruction of PTFE. The figure shows the IR spectra of composites based on PTFE before and after friction.

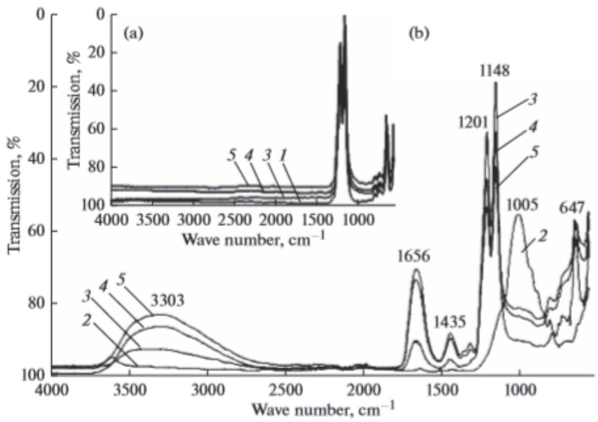

Figure. Typical IR spectra of PTFE composites before (a) and after friction (b)

In contrast to the spectra of the composites before friction (Fig. 1a), the spectra after friction are characterized by broad absorption bands in the region of 2800–3600 cm^{-1}, as well as by two characteristic intense bands at 1656 and 1435 cm^{-1}. It is obvious that these peaks refer to the stable products of tribooxidation of the carbon chain of PTFE that are formed on the friction surface of the composites. The appearance of wide bands in the region of 2800–3600 cm^{-1} indicates the presence of associates of OH-groups in the surface layer connected by hydrogen bonds. The following intense bands at 1656 and 1435 cm^{-1} are characteristic for anions of the salts of carboxylic acids, in this case perfluorocarboxylic anions. There are various mechanisms for the formation of carboxylate anions during tribooxidation. One of them is given in the work [1]. Another mechanism is the further oxidation of the hydroxyl group. The initiators of this chain of reactions are, obviously, the iron cations of the counterbody. The intensity of the formation of carboxylate anions as inhibitors of further oxidative processes may depend on the nature of the metal in the composition of the PTFE filler.

Acknowledgements. Research was supported by the Ministry of Education and Science of the Russian Federation under the State Task no. 11.1557.2017/4.6.

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MONITORING OF CHANGES IN SERVICE PROPERTIES OF LUBRICANTS IN TRANSMISSIONS OF TECHNOLOGICAL EQUIPMENT

Basiniuk V.L., D. Sc. in Eng.

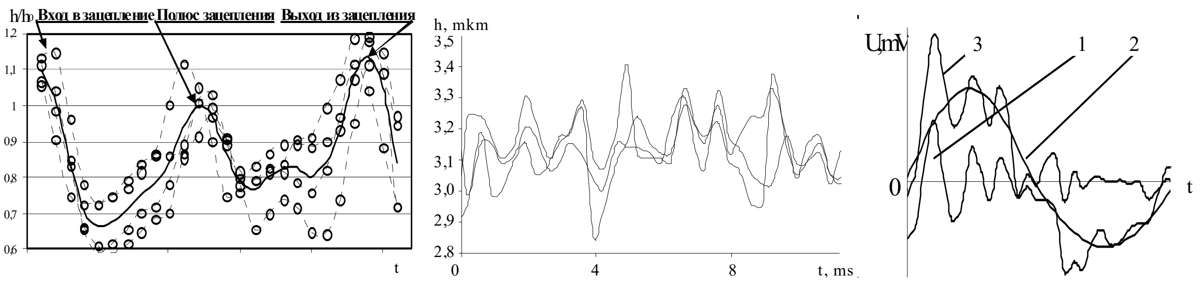
Joint Institute of Mechanical Engineering of the NAS of Belarus

Keywords: vibroacoustics; monitoring; oil film; forecasting; lifetime.

Introduction. Transmissions based on toothed gears remain one of the main components of the processing, including unique expensive equipment. Its cost in some cases reaches 1 million euros or more, and the service life before overhaul, modernization or replacement is 8...10 or more years. At the same time, the conditions of dynamic and frictional interaction of friction joints of the equipment may refer to one of the most important factors that have the most significant impact on the lifetime and energy efficiency in the operation of the equipment. These conditions, on the one hand, are determined by the speed, load, thermal modes of interaction and the topography of the working surfaces of friction joints, as well as by their change as the friction joints wear, on the other hand, by the service properties of lubricants and their degradation during operation.

Methods of solving the main tasks of research. To assess the possibility of indirect control of tribotechnical conditions of interaction of friction joints using the parameters of noise and vibration, the studies of the oil film thickness, noise and vibration were conducted in the operation of the gear [1] and the rolling bearing. The obtained data were processed and analyzed using the amplitude spectra of the presented parameters. Processing and analysis of the data were carried out by means of specialized software. In the analysis of the amplitude spectra, their composition was determined, and frequencies that are the most characteristic for the toothed gearing and significant in amplitude were distinguished. The analysis of the oscillograms of changes of the recorded parameters was conducted with turning of the gears on the angular increment and bearing – for shaft rotation.

Results of research and their discussion. Some results of studies of the relationship between the amplitude spectra of the oil film thickness fluctuations, noise and vibration accelerations, that make it possible to assess the possibility of using the monitoring of indirect means of control of tribotechnical parameters, are shown in figure.



a b c

Figure. Relative changes of thickness "*h*" of oil film with pair of teeth in gearing (a), changes of thickness "*h*" of oil film per revolution of bearing retainer (b), and oscillogram of voltage of vibration accelerations sensor, recording oscillations generated on bearing supports by a pair of teeth while turning on the angular increment (1 – sum of oscillations; 2 – free oscillations in toothed gearing; 3 – forced oscillations with gear-meshing frequency) (c)

Conclusion. Using the above approaches, an effective automated system for complex monitoring and control of operating modes of drives of expensive technically complex equipment can be created, combining direct and indirect means of controlling their dynamic, tribotechnical and lifetime parameters.

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MAGNETIC-ABRASIVE PROCESSING OF COATINGS ON THE BASIS OF NICKEL

F.I. Panteleenko[1], G.V. Petrishin[2], and V.M. Bystrenkov[2]

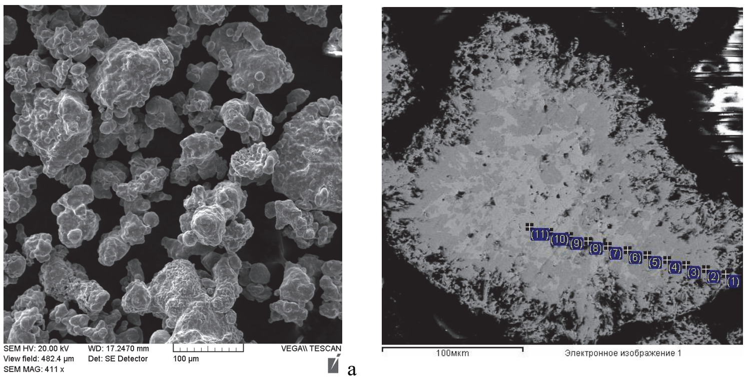
[1]Belarusian National Technical University, Minsk, Belarus, panteleyenkofi@tut.by
[2]Sukhoi State technical university of Gomel, Gomel, Belarus, petrishin@gstu.by

Keywords: magnetic-abrasive processing; roughness; powder.

The problem of finishing processing products with a curve profile often is solved by using the technology of magnetic-abrasive processing. The sintered powder materials, which consist a ferromagnetic base and abrasive inclusions are most often materials, used as an abrasive tool in this technology [1].

The purpose of this work is to study the effect of new borated abrasive powder materials on the productivity of magnetic-abrasive processing technology and the surface roughness of parts from churlish materials.

Materials and methods. The new borated powder materials were used as an abrasive tool, which have high magnetic properties due to the iron base and high surface hardness due to by iron borides FeB and Fe^2B (figure) [2]. The material to be processed is wear-resistant coatings of sintered Ni-Cr-B system alloys. The initial surface roughness was Ra 1.25 μm.



a б

Figure. The new borated powder from the dispersed metal wastes: a – morphology; b – the structure of particles

Result and discussion. In this work was established the influence of the fractional composition of the new powder tool to the process productivity and surface roughness. The use of powders with a particle size of 0.315...0.400 mm showed a processing capacity of 1.8...1.9 μm / min, ensuring a roughness of Ra 0.50 μm. The change in the fractional composition to 0.200...0.315 mm reduced the productivity to 1.7 μm/min, but allowed to obtain the required roughness Ra 0.32 μm. Increasing the processing time to 30 minutes allowed reducing the roughness to Ra 0.09 μm [3]. Studies have shown the high efficiency of new borated abrasive materials based on dispersed metal waste in the technology of magnetic-abrasive machining of sintered nickel-based materials. Provides high productivity processing and roughness up to Ra 0,09 microns

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SLIDING FRICTION IN BEARING UNITS OF PRECISION SYSTEMS

A.S. Kalinichenko[1], V.L. Basinyuk[2], and O.G. Devoino[1]

[1]Belarusian National Technical University, Minsk, Belarus, akalinichenko@bntu.by
[2]Joint Institute of Mechanical Engineering of NAS of Belarus, Minsk, Belarus, vladbas@mail.ru

Keywords: composite material; sliding friction; mechatronic system; antifriction coating.

The aim of this work is the rational design and manufacture of friction pairs based on coatings made of composite antifriction materials for high-speed machining systems. This is particularly important for vertical high-speed electrospindles for machining in electronic engineering, because they have high requirements for rigidity.

Sliding bearings with composite antifriction coatings are promising to provide high rigidity in the friction units of high-speed electrospindles. Aluminum alloys are of considerable interest for the manufacture of cooled components of the electrospindle with forced cooling from the standpoint of improving the dynamic properties and heat exchange during operation [1, 2]. This allows minimizing the weight of the spindle shaft and improves the heat transfer during cooling compared to steel one. In addition, the working surfaces of the sliding bearings can be formed directly on the electrospindle shaft, and to increase wear resistance of the unit composite antifriction coatings are formed on the working surfaces.

To realize these intentions, it is very important to develop methodological approaches to the rational design and manufacture of sliding friction pairs based on the composite antifriction materials' coatings for the application in vertical precision program-controlled electrospindles for high-speed machining. One of the promising ways of forming such coatings in the friction units of mechatronic drives is the implementation of the following technological scheme. Firstly, it is necessary to deposit a coating with a thickness of more than 70 µm by micro-arc treatment (MAT) on the working surfaces of sliding friction pairs. This thickness eliminates the "pushing" of the support surface and the occurrence of jamming in contact with abrasive particles. Next steps included operations of preparing the surface of the MAT-coating for subsequent cladding. Research and analysis of the results of the above scheme showed that, even after mechanical superfinish treatment of the MAT-coating's surface the topography of this surface remains sufficiently developed. Moreover, the microstructure of MAT-coating was characterized with porosity and even cracks. Mechanical treatment of the MAT-coating's surface layer removed most defective zone which reduces the adhesive strength of the coating deposited on the surface of the antifriction layer. Then the surface cladding of MDO-coating with antifriction material for example, nanostructured composite based on copper alloy, was applied using electron or laser beam. After the formation on the surface of sliding friction pair an additional antifriction layer with a thickness of 3–5 µm coated by plastic deformation is advisable.

The developed approach allows solving two problems in a complex:

– the rigidity of the electrospindle required for ultra-high accuracy of mechanical blade machining is achieved;

– provides high smoothness of machining allowing to achieve nanometric surface roughness, which is extremely important for a number of special applications.

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TRIBOLOGICAL MATERIALS BASED ON THERMOPLASTICS REINFORCED BY CHEMICAL FIBERS

A. Burya

Dniprovsk State Technical University, Kamyanske, Ukraine, e-mail ol.burya@gmail.com

Keywords: chemical fibers; thermoplastics; composite materials; organoplastics.

The strategy of development of the world chemical industry in the third millennium is characterized by the rapid growth of the polymer composite materials industry (PCM), the main directions of which are improving the quality of polymers and their processing methods, creating new plastics, and also expanding their application areas, in particular, in tribotechnics.

The purpose of presented work is development and research of scientific and technical bases for the creation and implementation of highly efficient and reliable structures and products that are surpassed foreign analogues in terms of technical and economic indicators and can be used for modernization of modern machines and mechanisms, including special equipment.

The object of research was PCM based on thermoplastic binders and chemical fibers.

For the first time, are revealed the basic regularities of the influence of content, nature, strength, modulus of elasticity, temperature of thermal processing of the fiber on characteristics of reinforced plastics. It is shown that the greatest decrease intensity of linear wear and the coefficient of friction is achieved by increasing the breaking strength of reinforcing organic fibers up to 40 gs/tex (for fusible thermoplastics) and 60 gs/tex (for thermostable polymers). It has been found that in order to achieve the optimal complex of tribotechnical and physico-mechanical characteristics, the content of reinforcing fiber will be the less, the closer by nature it is located to the binder.

It has been shown the features of the interaction of nanoelements carbon fiber (Me – CF) with the polymeric matrix, which made it possible to create carbon plastics (CP) with high wear resistance, strength, and flame resistance. By the impact on the improvement of listed properties, fibers are located in the following row:

Mg – CF; Al – CF; Zn – CF; Sn – CF; Fe – CF; Cu – CF; Pb – CF.

Composites of the second and the third generation. A promising direction for improving properties of composite materials (CM) is the creation on their basis CM of the second generation using hybrid binder or hybrid fillers (Fil). For example, the use of hybrid Fil, which includes in its composition superdispersed oxynitride silicon yttrium (OSY) and CF ensures CM high physico-mechanical properties. CM based on the phenylone containing hybrid Fil composition: OSY (1 wt.%) + CF, with the surface, modified by amino groups (17 wt.%) due to high tribological properties can be operated in conditions of friction without greasing at $p\upsilon < 8$ MPa·m/s. There is an increase of oxygen index up to 83%, hardness up to 340 MPa, wear resistance to $0{,}26 \cdot 10^{-8}$, and decrease of the coefficient of friction from 0.27–0.09 till 0.09–0.11 with the use of phosphorus-containing (7–25 wt.%) and phosphorus-lead-containing (10–15 wt.%) CF. Modification of carbonplastics by amino- and chloro groups leads to improvement of all complex operational characteristics of CM based on phenylone. At present, the actual effect and scope of the implementation of the CM is achieved through the wide introduction and use of specifications developed by the authors (TS 6-06-31-423-83; TS 6-06-31-424-83; TS 0493679-21-85) from the production of developed CM, and also antifriction materials based on the of aliphatic and aromatic polyamides in Dnipro, Zhytomyr, Zaporozhye, Kyiv, Melitopol, Sumy etc. (Ukraine), Svetlogorsk "Khimvolokno" (Belarus), Beijing "Beijing King-tech Co., Ltd", Harbin "Harbin TongDa Industrial Environmental Protection Automation Co., Ltd" (China) etc.

MACROSCALE SUPERLUBRICITY OF HYDRATED IONS

T. Han, C. Zhang*, and J. Luo

Tsinghua University, Beijing, China, chzhang@tsinghua.edu.cn

Keywords: superlubricity; hydrated ions; silica layer; zeta potential; hydration effect.

Introduction. Superlubricity, known as the state of vanishing friction or no resistance between two contacting and sliding surfaces, will play a significant role in energy saving, environmental protection, and increasing the lifetime of equipment. Superlubricity based on hydration lubrication provides a near-frictionless lubrication state for the extreme reduction of friction in aqueous conditions. Nevertheless, how to obtain the hydration superlubricity under macroscale conditions with higher load-carrying capacity still remains a challenge. The mechanisms governing macroscale superlubricity especially the growth activities and the specific contribution of the tribo-induced silica layer to the superlubricity are still not well comprehended.

Results and discussion. Friction coefficients as a function of time under lubrication of 50 mM chloride and potassium salt solutions were measured, as shown in Fig. 1. It is obvious that the friction coefficients of LiCl, NaCl, and KCl solutions are all around 0.005, which represents that these three different alkali metal chloride salt solutions could achieve superlubricity after running-in by H_3PO_4 solution (pH = 1.5). However, the friction coefficients of CsCl and NH_4Cl solutions are 0.014 and 0.025, respectively, which means these two chloride salt solutions could not achieve the superlubricity state, although these two lubricants could attain a low friction [1]. Therefore, it can be concluded that the superlubricity achieved by hydrated alkali metal ions is in high accordance with the hydration strength of these hydrated ions [2–4]. Fig. 1c showed that the friction coefficients of four different potassium salt solutions reduced to 0.005 after running-in with acid solution. It can be concluded that the superlubricity of the above monovalent salt solutions is mainly determined by cations rather than halogen anions.

The silica layer on Si_3N_4 balls generated during the tribochemical reaction was analyzed by X-ray photoelectron spectroscopy (XPS) and transmission electron microscopy (TEM) in order to reveal its thickness and structure, as shown in Fig. 2. It was found from the depth profiles that the thickness of silica layer on the Si_3N_4 ball after running-in with H_3PO_4 solution was about 6.0 nm, which was also confirmed by high-resolution TEM. The silica layer formed on the Si_3N_4 ball is believed to play a critical role in achieving superlubricity for KCl solutions between Si_3N_4 and sapphire surfaces.

Zeta potentials of three plates including SiO_2, Si_3N_4, and Si_3N_4-Silica were measured. As shown in Fig. 3, the sequence of zeta potential in neutral KCl solutions was as follows, SiO_2 < Si_3N_4-Silica < Si_3N_4. Therefore, it can be inferred that compared with Si_3N_4 surface, there will be more silanol or hydroxyl groups (Si-OH) connected with SiO_2 surface in KCl solution, which makes Si_3N_4-Silica more negatively charged. Therefore, it can be concluded that the silica layer formed by the tribochemical reaction during the acid running-in period makes the Si_3N_4 surface with a higher negative charge density in KCl solution. It can be found in Fig. 3(*B*) that the superlubricity could be obtained as long as the pH was no less than 5.5. When pH < IEP, the surfaces become positive charged, the surfaces cannot adsorb hydrated K^+ ions, which results in the friction increase. Therefore, only when the surface pairs are negatively charged will the KCl solution exhibit superlubricity.

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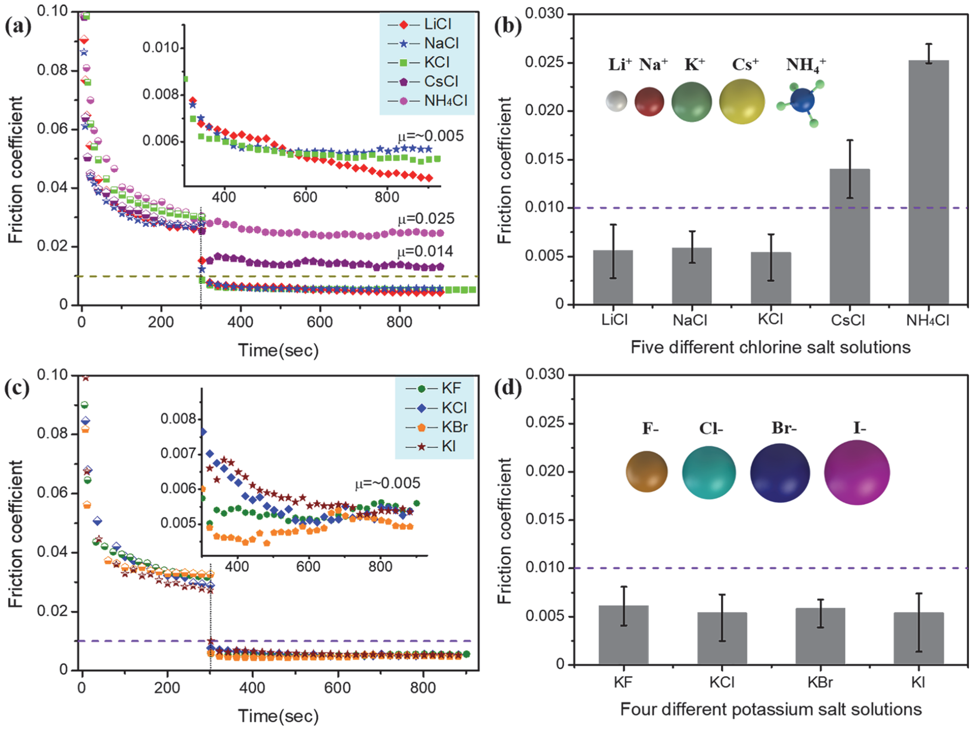

Fig. 1. Friction coefficients under lubrication of 50 mM chloride/potassium salt solutions

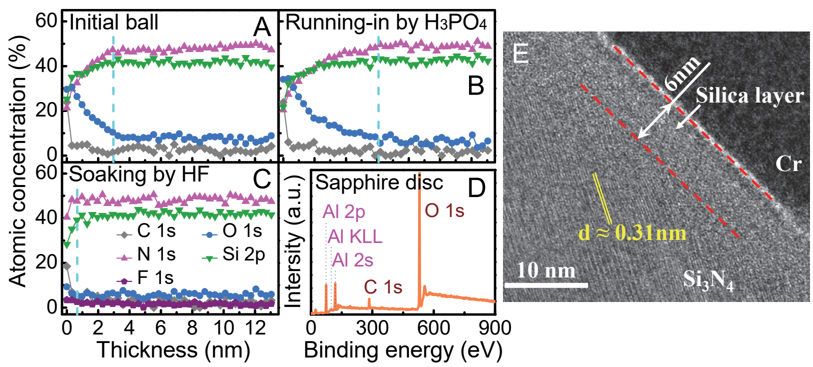

Fig. 2. Characterization of the wear region on the Si_3N_4 ball

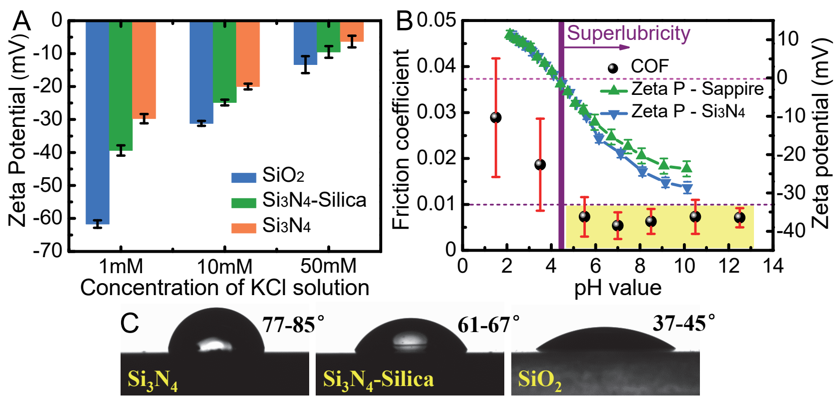

Fig. 3. Effect of the silica layer on the surface potential of Si_3N_4

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SOME FEATURES OF THE WEAR OF THE CAST ANTIFRICTION MATERIALS WITH MACROHETEROGENEOUS STRUCTURE

V.A. Kalinichenko

Belarusian National Technical University, Minsk, Belarus, kvlad@bntu.by

Keywords: antifriction materials; dry friction; wear; high specific load.

The aim of this work was to investigate the influence of specific loading on the wear of cast anti-friction materials with macroheterogeneous structure during dry friction. These materials have been developed for the manufacture of sliding bearings operating at high specific load and low sliding speeds.

Operation features of the developed sliding bearings (high specific load matched with low sliding velocity) do not allow providing hydrodynamic lubrication mode. Therefore, it is important to determine the effect of specific pressure on the wear resistance of the developed antifriction materials to expand their application. For studies samples were manufactured from bronze BrK3Mn1 reinforced with cast-iron granules by the method of liquid-solid synthesis.

The use of cast iron granules as a reinforcing phase allows for subsequent heat treatment to obtain a wide range of their microstructures. Different microstructure of the reinforcing phase provided a wide range of physical-mechanical properties and wear resistance. The tests were carried out according to the disk – rod scheme for the dry friction mode. The linear velocity of relative motion varied from 0.314 to 20.0 m/s, and the specific pressure varied in the range of 1.9...10.7 MPa.

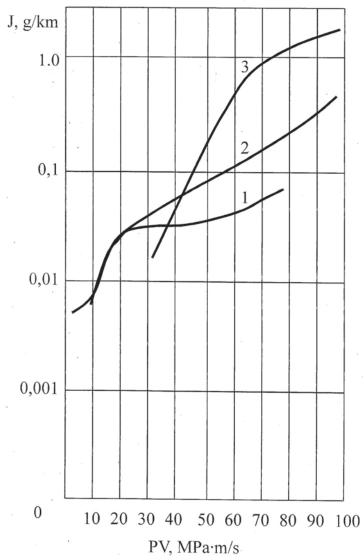

Figure. Dependence of wear for different specific load: 1 – 2.9 MPa; 2 – 7.6 MPa; 3 – 10.7 MPa

The steel 45 disc in the post-quenching state (HRC = 44...50) was used as a counterbody. The value pV characterizes the bearing capacity of antifriction materials. Therefore, the test results are shown in the form of the dependence of the wear on pV for various specific pressures (figure).

Analysis of tests showed that at a specific pressure of 2.9 MPa, the formation of scoring and setting between specimen material and counterbody were not observed for the entire studied range of pV values (up to 78 MPa·m/s). At a specific pressure of 7.6 MPa, the scoring on the friction surface and the setting of the specimens were observed when the value pV = 50 MPa·m/s was reached.

With an increase in the specific pressure to 10.7 MPa, the setting of friction surfaces and the formation of scoring were observed for pV values above 43 MPa·m/s. Moreover, higher wear resistance results were obtained for samples in which the reinforcing phase had a white cast iron structure.

The tests served as the basis for optimizing the structure of the composite material and the manufacture of sliding bearings, e.g. for the normalization of the thermal mechanical state of steam turbines [1].

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