Досліджено вплив трибоелектричних явищ на знософрикційні властивості металополімерних гальмівних поверхонь. Встановлено, що під час трибоелектричної взаємодії знософрикційні властивості поверхонь тертя фрикційних вузлів різних типів гальм залежать від різниці потенціалів в контакті фрикційних пар та величин електричних імпульсів струмів в гальмівних парах. Одержані результати дозволяють оптимізувати керування знософрикційними властивостями гальмівних вузлів

Ключові слова: металополімерні пари тертя, барабанно-колодкове гальмо, дискове гальмо, трибосистема, трибоелектричні процеси

Исследовано влияние трибоэлектрических явлений на износофрикционные свойства металлополимерных тормозных поверхностей. Установлено, что во время трибоэлектрического взаимодействия износофрикционные свойства поверхностей трения фрикционных узлов разных типов тормозов зависят от разницы потенциалов в контакте фрикционных пар и величин электрических импульсов токов в тормозных парах. Полученные результаты позволяют оптимизировать управление износофрикционными свойствами тормозных узлов

Ключевые слова: металлополимерные пары трения, барабанно-колодочный тормоз, дисковый тормоз, трибосистема, трибоэлектрические процессы

UDC 621.891
DOI: 10.15587/1729-4061.2017.91615

EXAMINING THE EFFECT OF TRIBOELECTRIC PHENOMENA ON WEAR-FRICTION PROPERTIES OF METAL-POLYMERIC FRICTIONAL COUPLES

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1. Introduction

Modern science has accumulated a lot of information on the wear mechanisms of frictional couples of braking devices, but the problem of revealing the nature of their friction interaction is far from the final solution. One reason stems from the fact that during the friction process as a result of electric phenomena in a friction contact of metal-polymeric tribological conjunction, there occur substantial changes in properties of the surface layers of materials. This significantly affects their tribological characteristics.

The papers of numerous scientists are devoted to studying triboelectric phenomena of metal-polymeric frictional couples of braking devices, however, many studies contain contradictory information, and a number of problems of the triboelectric friction interaction are left out of focus. In particular, the mechanisms of the influence of triboelectric phenomena on wear-friction properties of metal-polymeric frictional couples of braking devices have not been established yet. Establishing the regularities of triboelectric interaction between the frictional couples of brakes is relevant in terms of the implementation of new methods for increasing the wear-friction properties of metal-polymeric frictional couples of braking devices.

2. Literature review and problem statement

At present, research into friction processes during the contact of two metals, metals and semiconductors has been conducted in a rather wide range. Thus, article [1] explored triboprocesses under conditions of high-velocity friction, and paper [2] presented an analysis of friction under non-stationary operating conditions. Paper [3] focused on the questions of optimization of triboprocesses, and article [4] studied triboelectric phenomena during drilling process. Triboelectric processes during the friction of samples from one metal were examined in [5]. The magnitudes and directions of circulating tribocurrents during friction with lubricants and without them were established for different metals. The wear resistance was found to increase, on average, twice when using the means of tribocurrents reduction.

In paper [6], the triboelectric processes in frictional couples from homogeneous steel under dry friction conditions were examined. The main causes of electric currents arising during friction and cutting metals, the influence of electric properties, geometric parameters and modes of cutting on the magnitude of electric currents were analyzed. The means of compensation for wear of metal frictional couples by using electric phenomena for moving dispersed metals particles on the surface of the frictional contact were considered in [7]. A mandatory existence of electric fields during the friction contact of "metal – metal" couples was emphasized. Double electric fields arising in the contact in the presence of lubricants were studied.

Researchers pay considerable attention to electro-chemical processes during friction. Thus, in [8], the research into electrothermomechanic wear was done, which was explained from electrochemical positions, and the connections between wear resistance of metals and the magnitude of galvanoEMF were established. In [9], authors explored electrochemical processes that took place in the contact of metals with fluids, established the regularities of separating and moving of ions and considered the wear of metal surfaces from electrochemical positions, taking into account their grounded and insulated states. Paper [10] set the task of calculating electrical conductivity of the rough contact. The dependences for determining the electrical resistance of the area of the actual contact were proposed. Due to the complexity of determining the resistance of surface films, the established regularities appeared reliable mostly for noble metals.

Research into triboelectric processes in the couples "polymer-polymer" and in dielectrics was not so comprehensive.

Electric conductivity and strength of polymers and their resistance to surface discharges were explored in paper [11]. It was found that the conductivity of pure polymers is low. But with existence of destruction, dissociation products and contamination, the conductivity of polymers increases dramatically. The mechanism of circulation of electric currents through the contact of above-mentioned frictional couples is the result of the passage of electrons from the material with the lower work function of electrons to the material with higher work function and the characteristics of the frictional contact, which is the subject of a number of articles. Thus, in [12], the emission of electrons from the surfaces of solids during friction was studied. It was found that by data of work function of electrons from friction surfaces it is possible to assess the state and defects of surfaces, as well as to determine the level of surface energy. In [13], the influence of triboelectric phenomena on polymer destruction during friction was studied. It was revealed that polymer molecules are destroyed during friction, which creates the emission of electrons from surfaces.

Electrical properties of polymers were examined in [14]. It was found that the conductivity of polymers increases up to two orders in existence of copper compounds, and the sorption of water by a polymer leads to an increase in conductivity of polymers by several orders. The conductivity of a polymer was found to increase by orders at exceeding the melting temperature. Paper [15] provides an analytical description of circulating currents and studies electrical conductivity of polymers depending on the change in temperatures and pressures.

In terms of metal-polymeric friction couples, an analysis of relevant sources indicates the uncertainty of mechanisms of their triboelectrization and controversy of a large number of the known results. In this case, it is necessary to note that the surface condition for polymer linings and metallic friction elements is characterized by different physical nature.

Triboelectric phenomena in metal-polymeric frictional couples significantly affect mass transfer processes and composition of the boundary layer, which, in turn, determine the direction and magnitudes of tribocurrents. Thus, work [16] represents the impact of electrization phenomena on mass transfer processes in metal-polymeric frictional couples. Both the formation of polymer films on the surface of metals and the transfer of metals on the surface of the polymer were studied. But there are only assumptions rather than explanations of the mechanism of change in triboEMF. In paper [17], authors examined the processes of hydrogenation in metal-polymer friction couples of tripper shoe brakes and fixed the increased wear of friction surfaces and a decrease in the effectiveness of braking. In articles [18, 19], the directions of tribocurrent circulation during the friction of metal-polymeric couples were studied. But the experimental data did not always agree with theoretical calculations.

Thus, it should be noted that there are rather ambiguous, contradictory and complex relationships between triboelectric processes and wear-friction characteristics, and the state of surfaces of metal-polymeric frictional couples.

3. The aim and tasks of the study

The aim of present work is to study the wear-friction properties of surface layers of metal-polymeric frictional couples, which are in the process of mechanical, thermal and electrical interaction, in the friction nodes of braking devices, taking into account the triboelectric phenomena.

To achieve this aim, the following tasks were to be solved:

– to explore the contact difference of potentials in frictional couples of braking devices with regard to mechanical and thermal gradients that occur in the surface layers of frictional couples;

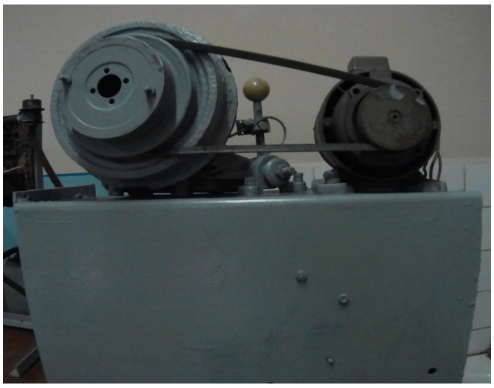
– to establish the influence of sliding velocity of friction surfaces of braking devices on the electrical and thermal currents and the influence of change in the types of surface contacts on the directions of current pulses in frictional couples of braking devices;

– to identify the connections of pulse currents in the surface layers of braking devices and temperature gradients in two- and three-layered structures.

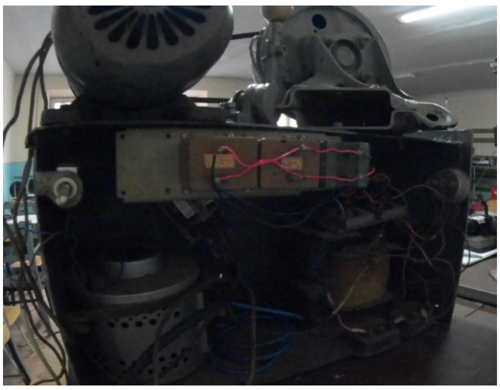
4. Materials and methods for studying triboelectric processes in metal-polymeric frictional couples

4. 1. Studied materials and equipment used in the experiment

Taking into account the tasks of the research, the brake stand with the model drum-block brake was designed and manufactured (Fig. 1). The stand was designed to establish the patterns of characteristics of electric and thermal currents during electrothermomechanic friction.



a



b

Fig. 1. General view of stand of the model drum-block brake: *a* – drum-block brake with electric drive; *b* – control desk with electropower part

To register the data of changes in the contact difference of potentials of frictional couples on a personal computer, the contact surfaces were connected to the laptop (Fig. 2) via the analog-to-digital converter of the computer oscillograph USB Oscilloscope (made in Ukraine). The obtained values of the contact difference of potentials of frictional couples were registered in real time, recorded on the hard disk of the computer and processed using the software of the computer oscillograph USB Oscilloscope.

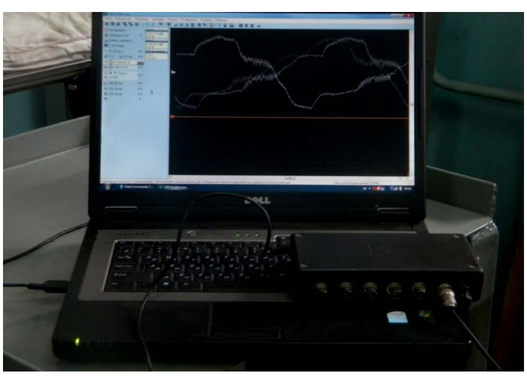


Fig. 2. Computer oscillograph USB Oscilloscope for determining the contact difference of potentials

4. 2. Methods of determining the indicators of triboelectric processes in metal-polymeric frictional couples

Conducting a sufficient number of tests of metal-polymeric frictional couples of braking devices under stand conditions allows objective judgments on wear-friction processes depending on the generated electric currents.

The task of the experimental research was to check the conceptual approach to the thermo-stimulated polarization and depolarization of the surfaces of metal-polymeric frictional couples of braking devices.

Based on the foregoing, the brake stands should meet the following requirements:

– executing single and lengthy braking for the estimation of currents and temperature on the surfaces of metal-polymeric frictional couples;

– simulation of actual operating conditions of frictional couples of brakes with the possibility to change tribological parameters of their surface layers.

In this case, the following parameters were to be registered:

– braking time and number of braking;

– temperatures and angular velocity of friction elements;

– strength of currents that circulate between the frictional couples;

– the differences in potentials between frictional couples.

5. Results of studying the wear-friction properties of friction couples of braking devices

The contact difference of potentials was established to consist of a constant and a pulse (or variable) component. The constant component depends, mainly, on the materials of contact surfaces and surface temperatures, while the pulse component mainly depends on the fluctuations of electro-thermal resistance in the contact and energy fluctuations of friction surfaces. The pulse component influences the wear-friction properties of frictional couples of friction nodes in more considerable degree, than the magnitude of the constant component of the contact difference of potentials. Fig. 3 illustrates the dependence of the pulse contact difference of potentials of the friction couples "steel 34 L – retinax FC –24" of the model brakes at temperature 320 °C, registered with the help of computer oscillograph USB Oscilloscope.

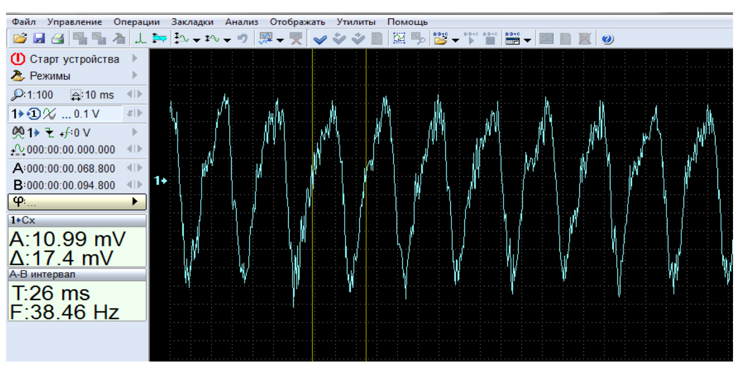
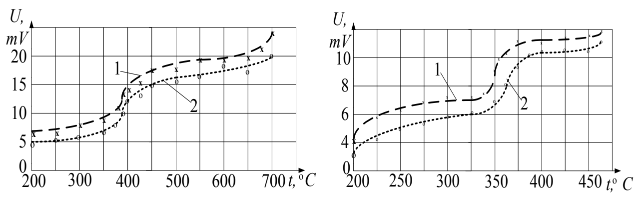


Fig. 3. Dependences of the contact difference of potentials of the frictional couples "grey cast iron CI 20 – cipher 1–43–60A" of the model drum-shoe brake at temperature 320 °C

The contact difference of potentials is largely affected by the surface temperature of contacting bodies. If one of the bodies is heated more, electronic or ionic thermo-currents are directed from it to the other body. The difference of potential also grows at an increase in the area of contacting bodies. The charges of contacting bodies have different signs, but the same magnitude. Fig. 4 provides the illustration of dependences of the constant component of the contact difference of potentials of frictional couples of brakes on the surface temperature of linings at different specific loads. As it can be seen from Fig. 4, for the frictional couple of grey cast iron CI 20 – polymer of 2141 cipher of the brakes, we have a situation where a metal friction element is positively charged relative to the friction linings.

An increase in potential in the contact at an increase of temperature of linings is explained by the fact that the energy level of electrons of the material of the metal friction element increases at heating. This, in turn, leads to an increase in the difference of potentials in the contact. It should be noted that a substantial increase in the potential in the contact is observed in the range of 380–400 °C. This is explained by the transition of phenol-formaldehyde resin to the liquid phase and a decrease in electrical resistance at the contact. At temperatures of 550–600 °C the intensity of an increase in potential in the contact falls. This is due to a decrease in the liquid phase in the contact, while at temperatures of approximately 700 °C and above the liquid phase disappears completely (burns out). This leads to an increase in electrical resistance in the contact and a decrease in the emission of electrons.



a *b*

Fig. 4. Dependences of electric potential of frictional couples on the surface temperature of linings: *a* — couple "gray cast iron GI 20 — polymer of 2141 cipher"; *b* — couple "gray cast iron GI 20 — cipher 1—43—60A"; 1 — at specific load of 0.5 MPa; 2 — at specific load of 0.7 MPa

As it follows from Fig. 4, *b*, for the frictional couple of grey cast iron GI 20 – 1–43–60A cipher of the drum-shoe brake, the brake drum is positively charged relatively to the friction linings. Some local decrease in potential in the contact in ranges of up to 330 °C and above 400 °C, at an increase in temperature of linings is explained by the fact that for the material of 1–43–60 A cipher of the lining, the energy level of electrons decreases at heating. This, in turn, leads to a decrease in difference of potentials in the contact. In this case, an increase in the potential in the range of 330–400 °C is explained, as in the previous case, by a sharp fall in electric resistance.

Under laboratory conditions for the frictional couple "steel 60 G – polymer of 2141 cipher", we obtained a dependence of electrization currents on the sliding velocity and time at specific loads p=0.2 MPa (Fig. 5).

The resulting diagram of the change in current in the friction couple "shoe – disk" showed that currents are quite unstable. In this case, the amplitudes of currents increase with an increase in sliding velocity. At the increase in sliding velocity, the inversion of current also increases and, in this case, the magnitude of current increases at the increase in time of interaction between friction couples. Directions and magnitudes of currents, generated at the surfaces of frictional couples, depend on the work function of electrons and ions from the surfaces of frictional couples.

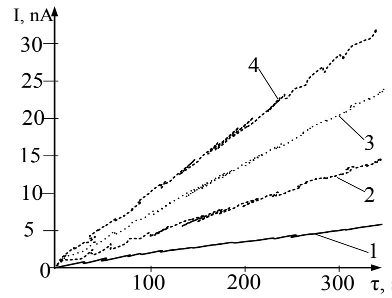


Fig. 5. Dependences of tribocurrents on time (τ) of frictional interaction of the couple "steel 60 G — polymer of 2141 cipher" at different sliding velocities: 1 — 0.8 m/s; 2 — 1.2 m/s; 3 — 2.0 m/s; 4 — 2.5 m/s

Let us focus on the examination of temperature dependences of electric current that flows through three-layered metal-polymeric structure. An important area of temperature dependences is the range of phase transition at the transition of phenol-formaldehyde resin from the solid to the liquid phase. In this case, a sharp increase in current is registered due to a decrease in electrical resistance of the contact. An example of registration of phase transition by the magnitude of current flowing through the three-layered structure "metal-polymer-metal" of the drum – shoe brake is shown in Fig. 6.

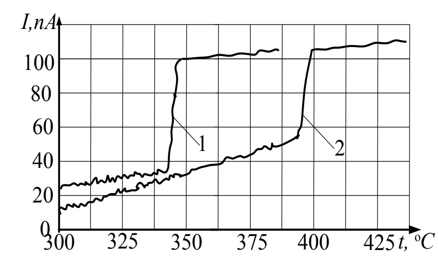


Fig. 6. Temperature dependence of current that flows through three—layered structure "metal (M_1) — polymer-metal (M_2)": 1 — grey cast iron GI 20 — polymeric material of 1—43—60 A cipher — steel 55; 2 — steel 34 L — cipher 6KF—59 — steel 50

Sliding velocity at specific loads of p=0.2 MPa was ν= =0.8 m/s, the heating rate of frictional couples was 5.0 °C/s. The vertical sections of the experimental curves correspond to melting temperatures of phenol-formaldehyde resin of the friction setting. It is possible to state how great the change of a measured parameter is the magnitude of the electric current that flows through the three-layered structure. At the temperature lower than temperature of the phase transition, one can see the fluctuations of current growing at an increase in temperature, the so-called transient fluctuations, which are explained in some papers by layer-by-layer monoatomic melting of the surface that precedes the volumetric phase transition.

Let us focus on the dependence of thermo-stimulated discharge of the structure (Fig. 7), consisting of two layers. The dependence was studied for the frictional couple "grey cast iron GI 20–2141 cipher". First, at the beginning of the friction process, the electrization process occurs at the given inter-phase boundary with the formation of a surface charge. Because for a given pair, the conduction currents in the upper and lower layers move towards each other, they pretty much neutralize the charge. Depending on which conductivity is higher, the discharge current can be positive or negative.

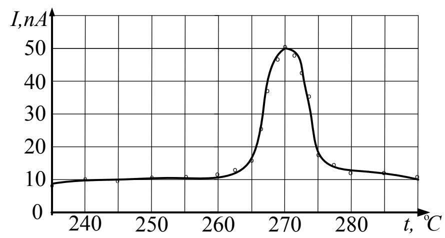


Fig. 7. Graphical dependence of discharge current generated in the contact of two-layer structures on the surface temperature at specific loads 0.4 MPa in couple "gray cast iron GI 20 — polymer of 2141 cipher"

Thus, the performed studies allow distinguishing the patterns of triboelectric interaction of metal-polymeric frictional couples of braking devices.

6. Discussion of results of studying triboelectric processes in metal-polymeric frictional couples

Conducted experiments are a continuation of research into triboelectric phenomena in meta-polymeric frictional couples and allow the expansion of the database on triboelectric processes in braking devices. As a result of the conducted studies of wear-friction properties of metal-polymeric frictional couples of braking devices under laboratory and operational conditions at the nano-, micro- and millilevel during triboelectric interaction, we established the regularities of changing thermo-stimulated discharge currents and electric potentials in the contact of frictional couples on the time of friction interaction, surface temperature of linings and specific loads.

The obtained results of triboelectric interactions are explained by the change of the electro-thermal resistance of discrete contacts of materials and various surface energies of contact materials in tribological conjunctions. During the contact-pulse friction interaction of metal-polymeric frictional couples, triboelectric and thermal currents are generated on their elements. The former are accumulated due to the Shottky effect (occurrence of current of electronic emission from the working surface of the metal friction element under the influence of electric field, which is created during the friction process), and the latter is the result of the thermo-electronic emission due to an increase in temperature of frictional couples.

The relationship between the generated currents is probably explained by the following. At the first stage of braking at low specific loads, there occur currents of electronic emission from the working surface of the metal friction element under the influence of electric field that is created during the friction process due to the triboeffect. At the increase in specific load, thermal current begins to be added to electric current, due to heat, which accumulates in the surface layers. At maximum specific loads, the area of contact surfaces and the surface temperature of the contact significantly increase and the generation mainly of thermal currents is observed. This causes a drastic increase in total electrocurrents.

7. Conclusions

Thus, as a result of the conducted research into wear-friction properties of metal-polymeric frictional couples of braking devices under laboratory and operating conditions during triboelectric interaction, the following regularities of changes were established:

– of magnitudes of the contact difference of potentials of friction couples "grey cast iron – polymers" of the drum-shoe brake on the surface temperature of linings and specific loads;

– of circulating thermal and tribocurrents on the time of friction interaction of frictional couples at different sliding velocities;

– of generated tribocurrents in the contact of two-layered structures "metal – polymer" and circulating tribocurrents through the three-layered structure "metal – polymer – metal" on the surface temperatures.

Obtained results allow the optimization of control the wear-friction properties and thermal state of braking nodes. Further research may be associated with the study of influence of triboelectric phenomena on wear and friction coefficients of friction surfaces of braking devices.

References

1. Sorokatyi, R. V. Analysis of processes of tribodamages under the conditions of high-speed friction [Text] / R. V. Sorokatyi, A. V. Dykha // Journal of Friction and Wear. – 2015. – Vol. 36, Issue 5. – P. 422–428. doi: 10.3103/s106836661505013x
2. Al-quraan Tareq, M. Evaluation Of Effectivness The Breaking-In Of Friction Pair In The Non-Stationary Work Conditions [Text] / M. Al-quraan Tareq, R. Mnatsakanov, O. Mikosyanchik, M. Khimko // Aust. J. Basic & Appl. Sci. – 2015. – Vol. 9, Issue 33. – P. 301–307.
3. Shatskyi, I. P. Strength Optimization of a Two-Layer Coating for the Particular Local Loading Conditions [Text] / I. P. Shatskyi, L. Ya. Ropyak, M. V. Makoviichuk // Strength of Materials – 2016. – Vol. 48, Issue 5. – P. 726–730. doi: 10.1007/s11223-016-9817-5
4. Dreus, A. Yu. Study on thermal strength reduction of rock formation in the diamond core drilling process using pulse flushing mode [Text] / A. Yu. Dreus, A. A. Kozhevnikov, A. K. Sudakov, Yu. N. Vakhalin // Naukovyy visnyk Natsional'noho Hirnychoho Unyversytetu. – 2016. – Issue 3. – P. 5–10.

5. Krawczyk, K. Możliwości sterowania siłą tarcia za pomocą prądu elektrycznego przepływającego przez strefę tarcia [Text] / K. Krawczyk, E. Nowiński, A. Chojnacka // Tribologia: tarcie, zużycie, smarowanie. – 2011. – Issue 2. – P. 61–70.
6. Chang, Y.-P. Trib-electrification mechanisms for self matedcarbon steels in dry severe wear process [Text] / Y.-P. Chang, J.-P. Yur, H.-M. Chou, H.-M. Chu // Wear. – 2006. – Vol. 260, Issue 11-12. – P. 1209–1216. doi: 10.1016/j.wear.2005.09.001
7. Janahmadov, A. K. The characteristic analysis of changes in the processes, phenomena and effects within working layers of metal polymer pairs during electro-thermo-mechanical friction [Text] / A. K. Janahmadov, A. I. Volchenko, M. Y. Javadov, D. A. Volchenko, N. A. Volchenko, E. A. Janahmadov // Science & Applied Engineering Quarterly (SAEQ). – 2014. – Issue 2. – P. 6–17.
8. Volchenko, A. I. Electro Mechanics Wear and Destruction of Brake Wheel Rims of Drilling Hoists (part 2) [Text] / A. I. Volchenko, N. A. Volchenko, M. Ya. Dzhavadov // Problems of Friction and Wear. – 2014. – Issue 3 (64). – P. 4–17.
9. Volchenko, A. I. Tribochemistry Processes and Phenomena in Superficial Layers of Brake Devices [Text] / A. I. Volchenko, N. A. Volchenko, P. A. Poliakov // Bulletin SevNTU. – 2011. – Issue 121. – P. 177–179.
10. Mamedov, R. K. Contacts of Metal-Semiconductor with Electric Field of Spots [Text] / R. K. Mamedov. – Baku: State University, 2013. – 231 p.
11. Galikhanov, M. F. Polymeric Composition Corona Charge Elects [Text]: abst. thes. ... doc. of eng. science / M. F. Galikhanov. – Kazan, 2009. – 35 p.
12. Levykin, D. A. Mathematical Model of Electric Contact of Rough Surfaces [Text] / D. A. Levykin // Software products and systems. – 2011. – Issue 4. – P. 178–180.
13. Kindrachuk, M. V. Wear of Friction Protective Straps at Contact-Impulsive Co-operation of Metal Polymer Friction Pairs of Band-Block Brake [Text] / M. V. Kindrachuk, H. A. Volchenko, D. A. Volchenko et. al. // Problems of Friction and Wear. – 2013. – Issue 2 (61). – P. 4–19.
14. Izmaylov, V. V. Contact of Solids and its Conductivity [Text] / V. V. Izmaylov, M. V. Novoselov. – Tver: university press TSTU, 2010. – 112 p.
15. Rozenbaum, V. M. Analytical Description of Currents of Thermostimulation Polarization and Depolarization [Text] / V. M. Rozenbaum, O. Ye. Tsmchik // Physics of solid. – 2010. – Vol. 52, Issue 10. – P. 2046–2051.
16. Volchenko, A. I. Tribology: Electrothermomechanic Bases, Analysis and Synthesis at Nano-, Mikro- and Millelevels and Technical Applications [Text]: textbook / A. I. Volchenko, M. V. Kindrachuk, D. A. Volchenko et. al.; A. I. Vol'chenko (Ed.). – Kyiv-Krasnodar, 2015. – 371 p.
17. Janahmadov, A. K. Band-block brake with conductive cooling [Text] / A. K. Janahmadov, A. M. Aliev, A. I. Volchenko, M. Y. Javadov // SRI researcher notes "Geotechnological Problems of Oil, Gas and Chemistry". – Baku, 2013. – P. 113–119.
18. Pashayev, A. M. The Multi-Fractal analysis of fatigue facture under friction the process [Text] / A. M. Pashayev, A. K. Janahmadov, O. A. Dyshin, M. Y. Javadov // Journal Science and applied engineering. – 2013. – Issue 01. – P. 5–20.
19. Pashayev, A. M. The Multifractal analysis of the fatigue fracture under the process of friction [Text] / A. M. Pashayev, A. Kh. Janahmadov, N. G. Javadov, M. Y. Javadov // WTC 2013, 5th World Tribology Congress. – Torino, Italy, 2013. – P. 8–13.