ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського
національного університету залізничного транспорту, 2018, № 3 (75)

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ

UDC 621.336

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PHYSICO-TECHNOLOGICAL ASPECTS OF WORK OF LUBRICANT FILMS IN THE TRIBOSYSTEM «OVERHEAD LINE – CURRENT COLLECTOR CONTACT STRIP»

Purpose. The article aimed at comprehensive analysis of the processes occurring in the lubricant films of the friction surfaces of the tribosystem «overhead line – current collector contact strip» (OLCCCS) and identification of the features of such systems. **Methodology.** The systematic analysis was used as the main methodology for studying the physico-technological aspects of work of the lubricant films in the tribosystem «overhead line – current collector contact strip». **Findings.** The theory of electro-friction interaction is now at such a stage that is characterized by a large amount of accumulated empirical data, hypotheses and models that cannot adequately represent phenomena in a sliding, high-current electrical contact. The sliding electrical contact of the tribosystem «overhead line – current collector contact strip» during the operation is affected by many factors, one of which is the processes in the lubricating layers of the friction pair. The work leads to a new level of understanding of the peculiarities of the processes occurring in the lubricating layers and their effect on the work of a sliding, high-current electrical contact, which can become the guarantee of significant increase in the efficiency of such systems and, as a consequence, substantially increase the reliability and safety of the work of the electric stock. **Originality.** It is proposed to consider the processes of electro-friction interaction of electrical contacts from the position of synergy using the theory of fractals as the core one for the quantitative description of self-organizing structures. **Practical value.** Taking into account the empirical experience of operation of the tribosystem «overhead line – current collector contact strip» in combination with theoretical knowledge allows us to propose three possible directions for solving tribological problems in high-current sliding electrical contacts. They are: 1) change in contact geometry and surface topography, for example, the use of regular macrorelief of contact surfaces; 2) development of conductive composites which are characterised with self-lubrication, for example the use of composite materials containing solid conductive lubricants; 3) development of effective lubricants for electric high-current sliding contacts, which may require some complication of the component design.

Keywords: contact pair; current collection; overhead line; wear rate; limit friction; contact transient resistance; current collector contact strip

Introduction

The «current collector – overhead line» system has an important task of transmitting energy from the power grid to the vehicle board. Consequently, a reliable electrical contact between the current collector and the overhead line is directly related to the reliability of operation and the safety of train movement. During operation, the overhead line and the contact strip of the current collector are exposed to multiple sliding friction, heating, erosion, etc., which makes the evolution of the contact quite complicated. An important role in the sliding contact operation is played by the antifriction lubrication.

Purpose

The main purpose of the work is a comprehensive analysis of the processes in the lubricant films of the friction surfaces of the tribosystem «over-

doi: 10.15802/stp2018/133323

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head line – current collector contact strip» (OLCCCS) and the identification of features of such systems.

Studies aimed at determining the peculiarities of the processes occurring in the lubricating layers of the friction surfaces of the tribosystem of OLCCCS should be considered relevant in scientific and practical terms, since taking into account these features can provide a significant increase in the efficiency of tribosystems of this class [3, 4, 14, 15].

Methodology

To achieve the purpose set forth in the work, it is envisaged to study the physico-technological aspects of the work of the lubricating layers in the tribosystem «overhead line – current collector contact strip». The system method is used as the main methodology.

Findings

The theory of friction and wear of surface layers under conditions of boundary lubrication was studied in the works by Kostetsky B. I. [7], Bauden F. P. and D. Tabor [5], Kragelskiy I. V. [8] Ahmatov O. S. [2], Chichinadze A. V. [13].

It is known that the work of sliding contacts is closely related to friction and wear. Therefore, it is necessary to consider not only the electrical properties of the sliding contacts, but also the phenomenon of friction and wear. In the general case, if the two purified surfaces are brought into contact at the interatomic distance, then the same gravity forces as in the volume of the material act between them. Several types of forces can be distinguished:

– ionic bond occurs between anions and cations that are held by electrostatic forces;

– covalent (homopolar) bond between neutral atoms is accomplished by overlapping their electron fields, which leads to the emergence of a strong bond;

– metallic bond is characteristic of all metals and is due to the presence of electrons, which move freely between the ion lattice sites;

– Van der Walsh bond can occur between any atoms or molecules due to dipole-dipole interaction.

Each atom in the material volume interacts with its closest neighbours by means of the above forces. The specific energy associated with this interaction is called cohesive energy and it plays an important role in the processes of friction and wear. Atoms on the surface have fewer neighbours, respectively, they do not have bonds outside the body (Fig. 1) [10]. For this reason, the surface of the solid has some impractical energy, which determines the surface's ability to form adhesive compounds.

The presence of surface energy causes the interaction of the surface with the environment (including with lubricants), which is called adsorption and leads to the formation of boundary layers. As a result of adsorption on the surface there are always elements of adjacent phases.

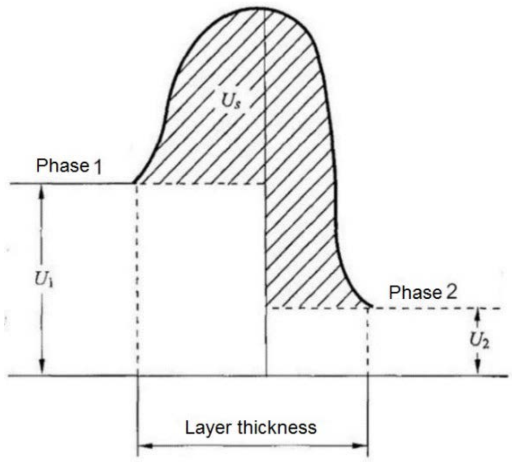

Fig. 1. Energy of boundary layer Us when contacting two phases 1 and 2, having the surface energy U1 and U2 (by Kashchev)

Physical adsorption is characterised with Van der Walsh interaction of adsorbate with the body surface. The polymolecular adsorption layers formed on the surface are relatively easily removed.

In the process of chemical adsorption, the energy of interaction is quite large, and on the surface there is usually formed a monolayer that is difficult to remove.

Thus, the adsorption activity of surfaces leads to the fact that they form a thin boundary layer, which differs in structure and properties from the surface (transition) layer of a solid. The physical state of matter of such a boundary layer may be different and depends both on the parameters of the state (temperature, pressure, etc.) and on the nature of the interaction with the solid phase.

Adhesion of the rubbing surfaces in many respects determines the patterns of friction and wear. Surface layers undergo various changes during friction; these changes can be both inverse and irreversi-

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ble, causing wear, seizure and other phenomena.

The primary source of these processes, and in some cases the main reason, is the stress-deformed and the thermal state of frictional contact.

Friction in the conditions of boundary lubrication is accompanied by the formation between the working surfaces of a thin layer of lubricant, which acquires the properties of the «third body» (according to Kragelskyi I. V. [5, 8]).

According to DSTU 2823-94, the term «boundary friction» is to be understood as «lubrication in which conditions of friction and wear of surfaces moving in relation to one another are determined by their properties, as well as by the properties of the lubricant, which differ from the bulk viscosity of the lubricant material».

The term «lubricating layers» of lubricants still has no unambiguous interpretation within the limits of DSTU, but in generalized form it is interpreted as follows: the lubricating layers of lubricants on solid lyophilic surfaces are «quasicrystalline molecular layers with a multimmolecular epitropon-liquid-crystalline structure» [1].

The lubricant in the boundary layer is anisotropic, so the molecular layers in the tangential direction slip one relative to the other. In the normal direction to the surface of friction the bearing capacity of the boundary layer is high and the deformation of its compression is within the limits of elasticity.

Friction with a semifluid lubricant occurs in the case of simultaneous action of liquid and boundary lubrication. The normal load is balanced by the compression resistance of the lubricant film in contact spots and the forces of hydrodynamic pressure in the layers of lubrication. The share of the reaction of boundary or liquid lubricant depends on the load, the speed of the mutual slip of the surfaces, the state of the surfaces, as well as the amount and viscosity of the lubricant. The hydrodynamic effect of the lubricant is manifested when it enters the macrogeometric gap between the friction surfaces.

To date, a wide range of models of tribological systems (friction without transmission of electric current) has been considered in detail, and a system of indicators of contact interaction, as well as methods for their determination, has been developed. The geometric characteristics of surfaces are introduced: macro-deviation, wavelength, roughness, submicroroughness; characteristics of contact areas – visible, contour, actual; types of contacts – elastic, elastic-plastic, plastic, etc. [13].

One of the contact elements (overhead line) is made of metal in the friction pair of OLCCCS, the main material of the second contact element (current collector contact strip) is solid-lubricating electrically conductive compositions of four basic types: metal graphite, graphite, carbon graphite and electro-graphite. Such compositions are characterised with the formation of friction of transferred films on a metal counterbody.

Experimental studies have shown that the thickness, composition and structure of the transferred films are interrelated with the external parameters of the sliding contact (load, speed), composition of the composite, counterbody and the environment [11]. At the same time, the film determines the mechanism of passing the current, and, respectively, the electrical characteristics of the contact, the nature and intensity of heat dissipation. The film thickness and the degree of coating of the metal counterbody inequality are, from this point of view, the most important factors of its effect, as illustrated in Fig. 2.

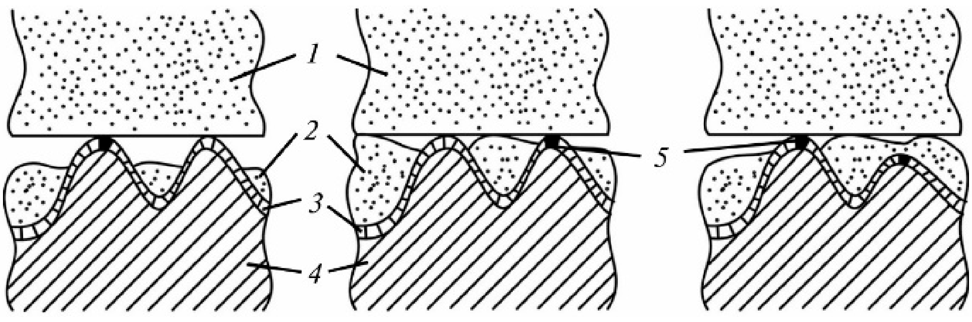

Fig. 2. Models of transition layer on the metal surface oxidized when working in pairs with self-lubricating contact material:
1 – self-lubricating contact material; *2* – transferred material; *3* – film of oxides; *4* – metal; *5* – areas with tunnel-conductive or destroyed oxide film

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The electric current can be considered as an additional external parameter of the tribosystem, which affects all characteristics of the sliding contact. This effect in many cases is so significant that the concept of «lubricating action» of electric current (reduction of frictional force with increased current density) and «electrical» wear (excessive wear of elements of a sliding contact in comparison with so-called mechanical wear in the absence of current) are specially introduced.

In carbon graphite and electro-graphite overlays, the increase in the current density, which passes through the contact, as a result of heat dissipation, reduces the strength of the surface layer and its shift resistance that results in the effect similar to the lubricant introduction into the contact. This effect is reversed.

For graphite brushes having a relatively high (up to 25% by weight) content of non-carbonated (polymeric) binder, the «lubrication effect» above a certain critical current density is irreversible and is expressed rather sharply, since heat dissipation causes the destruction of the binding material and composition.

When applying metal-graphite materials with high metal content (weight percent – up to 90%), the effect of current density on the friction coefficient is practically non-existent and only with high current density (more than 20 A/cm^2) the friction coefficient increases slightly. In such materials, the amount of transferred material on the counterbody is insignificant, and the frictional behaviour of such compositions is close to the behaviour of metals.

It is difficult to predict the intensity of contact wear by the current density magnitude due to the variety of current factors and the complex nature of their interconnection. The main factors of wear in the absence of electric sparking and arc formation are as follows: oxidation of the metal element of friction pair; growth of adhesion due to the dissociation of films of water or organic matter under the action of current; oxidation of the composite element of friction pair and weakening of its strength; emergence of shock-thermal stresses in a dynamic contact due to the uneven distribution of the current density in it [9, 11, 12]. All factors can act simultaneously and their main root cause is the heat release on the transient contact resistance. In the case of sparking or arc formation, the listed factors are added with electroerosion and emissions of contact material in the arc discharge, which increase the intensity of wear.

In the contact, the total surface of the section is divided into many individual spots. In this connection, when the energy flow passes through such a surface there is the additional resistance introduced by the violation of the homogeneity of the flow lines – the constriction resistance. It is added, in general, with resistance of the films of the following varieties: adhesive films, passive films, tarnish films (oxide, sulfide), water films, films from wear products [6].

Each component of the heterogeneity of the contact zone corresponds to the component of the total constriction resistance [6]. Holm proposed to take into account the two components, corresponding to the constriction to the group of spots and constriction within the boundaries of this group. For bodies with the same specific resistance ρ, which have one group of round, uniformly distributed spots, the following expression is obtained:

$$R_c = R_1 + R_2 = \rho \cdot \left(\frac{1}{2na} + \frac{1}{2a_k} \right), \quad (1)$$

where n – total number of contact spots; a – spot radius; a_k – radius of circle encompassing the contact spots; R_1, R_2 – components of resistance, which correspond to the constriction of spots and their groups.

Greenwood [16] clarified the second term of expression (1):

$$R_c = R_1 + R_2 = \rho \cdot \left(\frac{1}{2na} + \frac{16}{3\pi^2 a_k} \right), \quad (2)$$

and it is shown that its value is practically the same for any placement of contact spots in the general group.

The Greenwood formula has also been expanded by members that take into account the asymmetry of the distribution of groups of spots on each other, as well as the distribution of groups on the nominal area [18].

In the process of current collecting, the overhead line and the contact element are heated, with the importance of the relationship between the energy of the losses (A_l) and the heat dissipation (A_{hd}) that is released into the environment. With

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a certain limit value ΔA= Al – Ahd, the preconditions are created, which leads to plastic deformation of the contact surfaces with subsequent melting.

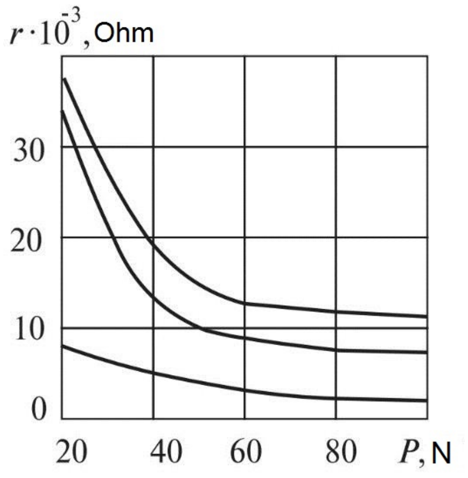

Fig. 3. Dependence of transient resistance on the pressing force for different materials

One of the main indicators of the quality of electrical contact is the drop in voltage ΔU on it:

$$\Delta U = I \cdot r \,, \tag{3}$$

where I – current through contacts, r – transient resistance of the contact pair.

Of course, the value of the transient resistance of the contact pair of OLCCCS is affected by the contact press; the change of the contact pressure even within the permissible limits is accompanied by a change in the transient resistance, illustrating the dependence on Fig. 3 [11].

Increasing the transient resistance of the contact pair, for one reason or another, leads to growth of ΔA.

An increase in the actual contact area in the friction pair helps to reduce the transient resistance r. Thus, using contact resistance and topography relationship data, we can give recommendations for constructing contacts, for example, the use of a regular macrorelief of contact surfaces.

From the standpoint of materials, several methods are used to improve the reliability of sliding contacts and their life extension. Common to them is the use of contact materials with a thin transition layer, for example the use of composite materials containing solid electrically conductive lubricants. The problem of developing lubricants for sliding contacts with relatively high speeds is currently not resolved.

The theory of electro-friction interaction is now at such a stage that is characterized by a large amount of accumulated empirical data, hypotheses and models that cannot adequately represent phenomena being studied. To date, the theory of self-organized systems – synergetics and the theory of fractals – self-similar evolutionary structures are rapidly developing, which are not described within the framework of Euclidean geometry.

Synergetics studies the processes of self-organization, stability and decay of structures of different nature, which are formed in open systems, an ordered state associated with the coordinated behaviour of subsystems. This leads to the formation of organized structures as a result of the exchange of energy and matter with the environment, when the equilibrium between production and reduction of entropy is established. The theory of fractals is the basis for the quantitative description of self-organizing structures [17, 19].

Originality and practical value

So far there is no single point of view concerning the problem of the mechanism of transmission of electric current through a sliding contact.

The qualitative development of the theory of electrical contacts can give consideration to the processes of electro-friction interaction from the position of synergy and the theory of fractals. Since the sliding electric contact is an open system, and in the transition layer, the evolutionary processes of the origin and collapse of conductor clusters take place.

In the technological aspect, three main directions of solving tribological problems in electrical contacts can be distinguished: change in contact geometry and surface topography; development of conductive composites for which self-lubrication is characteristic; development of effective lubricants for electrical contacts.

Conclusions

The work leads to a new level of understanding of the peculiarities of the processes occurring in the lubricating layers and their influence on the work of the moving electrical contact.

doi: 10.15802/stp2018/133323

Consideration of the processes of electro-frictional interaction of sliding contacts from the position of synergetics, where the theory of fractals is the basis for the quantitative description of structures, will contribute to the qualitative development of the theory of electrical contacts, which in practical terms can ensure the significant performance enhancement of such systems.

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doi: 10.15802/stp2018/133323

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ФІЗИКО-ТЕХНОЛОГІЧНІ АСПЕКТИ РОБОТИ ЗМАЩУВАЛЬНИХ ШАРІВ У ТРИБОСИСТЕМІ «КОНТАКТНИЙ ПРОВІД – КОНТАКТНА ВСТАВКА СТРУМОПРИЙМАЧА»

Мета. Головною метою роботи є всебічний аналіз процесів, що відбуваються в змащувальних шарах поверхонь тертя трибосистеми «контактний провід – контактна вставка струмоприймача» (КПКВС) та виявлення особливостей, характерних для систем цього класу. **Методика.** Для вивчення фізико-технологічних аспектів роботи змащувальних шарів у трибосистемі «контактний провід – контактна вставка струмоприймача» в якості основної методології застосовується системний аналіз. **Результати.** Теорія електрофрикційної взаємодії зараз перебуває на такому етапі, який характеризується великою кількістю нагромаджених емпіричних даних, гіпотез і моделей, котрі не можуть адекватно представити явища в ковзному сильнострумовому електричному контакті. Ковзний електричний контакт трибосистеми «контактний провід – контактна вставка струмоприймача» під час експлуатації піддається впливу багатьох факторів, одним із яких є процеси в змащувальних шарах пари тертя. Розуміння особливостей процесів, що протікають в змащувальних шарах, та їх впливу на роботу ковзного сильнострумового електричного контакту може стати запорукою забезпечення суттєвого підвищення працездатності таких систем і, як наслідок, суттєво підвищити надійність і безпеку роботи електрорухомого складу. **Наукова новизна.** Пропонується розглядати процеси електрофрикційної взаємодії електричних контактів з позиції синергетики, застосовуючи теорію фракталів в якості базової для кількісного опису структур, що самоорганізуються. **Практична значимість.** Урахування емпіричного досвіду експлуатації трибосистеми «контактний провід – контактна вставка струмоприймача» в поєднанні з теоретичними знаннями дозволяє запропонувати три можливих напрямки вирішення трибологічних проблем у сильнострумових ковзних електричних контактах. А саме: 1) зміну геометрії контакту й топографії поверхонь, наприклад, використання регулярного макрорельєфу поверхонь контакту; 2) розробку електропровідних композитів, для яких характерне самозмащування, наприклад, використання композиційних матеріалів, що містять тверді електропровідні мастила; 3) розробку ефективних мастил для електричних сильнострумових ковзних контактів, що може потребувати деякого ускладнення конструкції вузла.

Ключові слова: контактна пара; струмознімання; контактний провід; інтенсивність зношування; граничне тертя; перехідний опір контакту; контактна вставка струмоприймача

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ФИЗИКО-ТЕХНОЛОГИЧЕСКИЕ АСПЕКТЫ РАБОТЫ СМАЗОЧНЫХ СЛОЕВ В ТРИБОСИСТЕМЕ «КОНТАКТНЫЙ ПРОВОД – КОНТАКТНАЯ ВСТАВКА ТОКОПРИЕМНИКА»

Цель. Главной целью работы является всесторонний анализ процессов, происходящих в смазочных слоях поверхностей трения трибосистемы «контактный провод – контактная вставка токоприемника» (КПКВТ) и выявление особенностей, характерных для систем этого класса. **Методика.** При изучении физико-технологических аспектов работы смазочных слоев трибосистемы «контактный провод – контактная вставка токоприемника» в качестве основной методологии применяется системный анализ. **Результаты.** Теория электрофрикционного взаимодействия сейчас находится на этапе, характеризуемом большим количеством накопленных эмпирических данных, гипотез и моделей, которые не могут адекватно представить явления в скользящем сильноточном электрическом контакте. Скользящий электрический контакт трибосистемы

doi: 10.15802/stp2018/133323

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського
національного університету залізничного транспорту, 2018, № 3 (75)

«контактный провод – контактная вставка токоприемника» в процессе эксплуатации подвергается воздействию многих факторов, одним из которых являются процессы в смазочных слоях пары трения. Понимание особенностей процессов, протекающих в смазочных слоях и их влияния на работу скользящего сильноточного электрического контакта, может стать залогом обеспечения существенного повышения работоспособности таких систем и, как следствие, существенно повысить надежность и безопасность работы электроподвижного состава. **Научная новизна.** Предлагается рассматривать процессы электрофрикционного взаимодействия электрических контактов с позиции синергетики, применяя теорию фракталов в качестве базовой для количественного описания самоорганизующихся структур. **Практическая значимость.** Учет эмпирического опыта эксплуатации трибосистемы «контактный провод – контактная вставка токоприемника» в сочетании с теоретическими знаниями позволяет предложить три возможных направления решения трибологических проблем в сильноточных скользящих электрических контактах. А именно: 1) изменение геометрии контакта и топографии поверхностей, например, использование регулярного макрорельефа поверхностей контакта; 2) разработка электропроводящих композитов для которых характерно самосмазывание, например, использование композиционных материалов, содержащих твердые электропроводящие смазки; 3) разработка эффективных смазок для электрических сильноточных скользящих контактов, что может потребовать некоторого усложнения конструкции узла.

Ключевые слова: контактная пара; токосъем; контактный провод; интенсивность износа; предельное трение; переходное сопротивление контакта; контактная вставка токоприемника

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Prof. A. M. Mukha, D. Sc. (Tech.) (Ukraine) recommended this article to be published

Received: Feb. 14, 2018
Accepted: May 24, 2018

doi: 10.15802/stp2018/133323