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Nanostructures in the formation of the properties of high-current sliding electrical contacts on the electric rolling stock

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***Abstract*—The paper presents the results of bench tests of wear resistance of contact inserts of current collector runners made of «ROMANIT-UVLSh» material and their effect on the wear of the copper contact wire is evaluated. This material is a composite with a high content of electrically conductive lubricants capable of forming a thin conductive transition layer in a friction pair. Low temperature in the contact zone, indirectly, indicates a low transition resistance and high energy performance of the sliding contact, and low wear of the contact wire confirms its high tribological and mechanical properties. The use of contact inserts runner's current collectors made from this material is possible, both in alternating and direct current and can provide higher technical and economic indicators in comparison with traditional materials.**

Keywords—contact pair; current collection; contact wire; wear rate; boundary layer; contact insert current collector; protective film; fullerene

Introduction

The classification of electrical contacts can be carried out according to constructive-technological, kinematic, geometrical or other signs, but a whole class of electrical contacts is separately distinguished, whose work is accompanied by processes of friction and wear [1]. This class includes all sliding electrical contacts including vehicle electrical current collectors. At the moment, contact current collection systems for electric rolling stock are widely spread and used as a means of transmitting electrical energy to the electric rolling stock. As part of increasing the efficiency of operation of railway electrified transport, the task is to increase its speed, which in turn requires the improvement of existing and the creation of new devices that would ensure reliable and economical transmission of electric energy to a vehicle [2, 3], which implies a reduction wear of the contact wire and cases of its destruction, increasing the life of the runners of current collectors and reducing losses during the current collection.

Objective

Comprehensive analysis of the current collector pads made using innovative materials and technologies. The study of the mechanism of influence on the amount of wear of the contact wire according to the results of bench tests.

Main part

The system "current collector – contact wire" performs the most important task of transmitting electrical energy to the vehicle. Thus, reliable electrical contact between the skid plate of the current collector and the contact wire is directly related to the reliability of work and the safety of trains. In turn, the contact wire is an essential element of the contact network, and it is not redundant, and the trouble-free operation of electrified railways depends on its operation. During operation, it wears out, is damaged as a result of erosion, the action of high temperatures, mechanical loads. The relatively short life of the copper contact wire is determined not only by its wear, but also by the high probability of a break, which is associated with weakening and loss of tensile strength when heated, and this is especially important for high-speed lines, since the contact wires of their networks initially have greater tension for provide current collection conditions. All of the above is the cause of a sufficiently large amount of damage to the contact wire, with each damage leading to a break in movement, on average, for 2 hours [4], which is accompanied by additional significant material losses.

The operation of a high-current sliding electrical contact, in contrast to the friction units widely used in practice, is accompanied by the action of an electric current on external friction processes. Moreover, the performance of the sliding contacts associated with their wear is mainly determined by the processes occurring in the surface layers of friction pairs of ordinary tribosystems.

The flow of electric current through the surface of friction pairs leads to an increase in their heating, an increase in the

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kinetics of the flow of chemical reactions, the transfer of metals due to electrical phenomena. In this case, the high local temperature is explained by the high current density in α-spots, due to their small area.

All factors affecting the performance of high-current sliding electrical contacts can be divided into three main groups:

1. structural (profile of the wire section, the number of pads on the current collector's runner, type of suspension, type of reinforcement of the suspension);
2. metallographic (contact material, type of lubricant);
3. operational (sliding speed, the forces acting on the contacts, the amperage, the influence of the environment).

In this paper, the focus will be on factors belonging to the second group. In the most general case, if two cleaned surfaces are brought into contact at an interatomic distance, then the same forces act between them as in the bulk of the material. There are several types of such forces:

1. ionic bond;
2. covalent bond;
3. metallic bonding is characteristic of all metals and is due to the presence of electrons that are freely moving between the nodes of the crystal lattice;
4. Van der Waltz bond can occur between any atoms or molecules due to dipole-dipole interaction.

Each atom in the bulk of the material interacts with its closest neighbors using the above forces. The specific energy associated with this interaction is called cohesion energy, and it plays an important role in the processes of friction and wear. Atoms on the surface have fewer number of neighbors, respectively, they have no bonds beyond the boundaries of the body [5]. For this reason, the surface of a solid has some excess energy, which determines the ability of the surface to form adhesives. The presence of surface energy causes the interaction of the surface with the environment (including lubricants) – adsorption, and leads to the formation of boundary layers. Moreover, for physical adsorption, the Van-der-Waltz bond of the adsorbent with the body surface is characteristic and the polymolecular adsorption layers formed on the surface are rather easily removed. In the process of chemical adsorption, the interaction energy is substantially larger, and a monolayer is formed on the surface, which is much more difficult to remove.

Thus, the adsorption activity of surfaces leads to the formation of a thin boundary layer on them, which differs in structure and properties from the surface layer of the solid.

The adhesion of friction surfaces largely determines the patterns of friction and wear. The surface layers in the process of friction change and these changes can be both reversible and irreversible, and cause wear and tear, and other phenomena.

Friction in the conditions of boundary lubrication is accompanied by the formation of a thin layer of lubricant between the working surfaces, which has the properties of a "third body" (according to Kragelsky [6, 7]). The lubricant in the boundary layer is anisotropic, so the molecular layers in the tangential direction slide one relative to one. In the normal direction to the friction surface, the bearing capacity of the boundary layer is high and its compression deformation is within elastic limits. Friction may be accompanied by semi-fluid lubrication in the case of simultaneous action and liquid and boundary lubrication. In this case, the normal load is balanced by the compressive strength of the lubricant film at the points of contact (α-spot) and the hydrodynamic pressure forces in the lubricant layers. The proportion of a particular lubricant depends on many factors (load, sliding speed, condition of the surfaces, amount and viscosity of the lubricant). Under certain conditions, the lubricant may exhibit its hydrodynamic effect. In the contact pair "pad of the current collector skid – contact wire" one of the elements (contact wire) is made of metal, solid lubricating conductive compositions of four main types are used as the other contact element: metal graphite, graphite, carbon-graphite and electrographic. For such compositions, the creation of friction films on a metal counterbody is characteristic.

Experiments have shown that the thickness, composition, and structure of portable films are related to the external parameters of the sliding contact (load, velocity), the composition of the composite, the counterbody, and the environment [1]. With all this, the film determines the mechanism of transmission of electric current, and therefore the electrical characteristics of the contact, the nature and intensity of heat generation.

The thickness of the film and the degree of coverage of the irregularities of the metal counterbody are, from this point of view, the most important factors of its influence, which is illustrated in fig. 1.

Electric current should be considered as an additional external parameter of the tribosystem, which affects all the characteristics of the sliding contact. This effect is so significant that the concept of "lubricating effect" of electric current (reduction of friction force with increasing current density) and "electric" wear (excessive wear of sliding contact elements in comparison with mechanical wear in the absence of current) was specifically introduced.

In carbon-graphite and electrographite inserts, an increase in current density through the contact, due to heat generation, reduces the strength of the surface layer and its shear resistance, which causes an effect similar to bringing a lubricant into contact [1]. This effect is reversible.

For graphite linings that have a relatively high (mass fraction up to 25 %) Content of non-carbonated (polymeric) binder, the "lubricating effect" when exceeding a certain

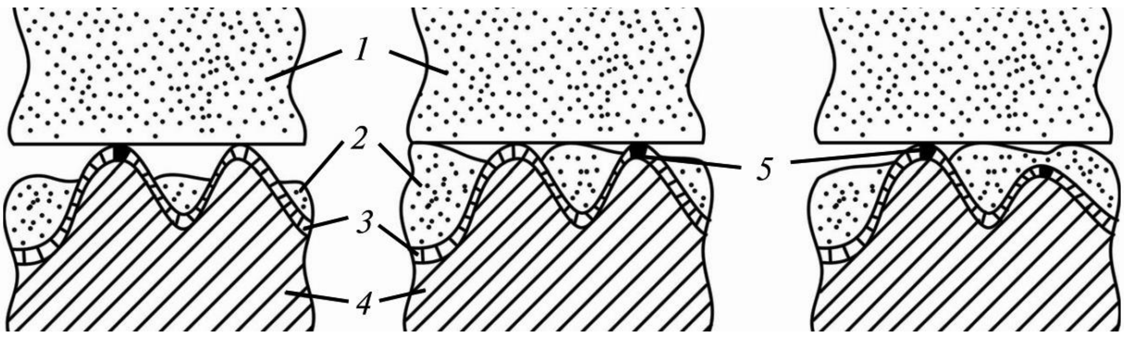


Fig. 1. Models of the transition layer on the metal surface oxidized when working in pairs with contact material with the ability to self-lubricate: 1 – contact material with the ability to self-lubricate; 2 – transferred material; 3 – a film of oxides; 4 – metal; 5 – areas with tunnel-welded or destroyed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

critical value of current density is irreversible and is pronounced sharply, as a result of heat generation binder is destroyed [1].

For metal graphite materials with a high metal content (mass fraction up to 90%), the effect of current density on the friction coefficient does not practically manifest itself and only at high current density (more than 20 A/cm^2) the coefficient of friction slightly increases. In such materials, the amount of material transferred to the surface of the counterbody is insignificant, and the frictional behavior of such compositions is very close to the behavior of metals.

But it is difficult to use the value of current density to predict the contact wear rate due to the diversity of current factors and the complex nature of their interaction with each other. Among the main factors of wear in the absence of electric sparking and arcing: oxidation of the metal element of a friction pair; oxidation of the composite element of a friction pair and weakening of its strength; increase in adhesion due to dissociation of water films or organic substances under the action of electric current; the occurrence of shock thermal stresses in dynamic contact through the uneven distribution of current density in it, a high coefficient of friction in the contact zone [8, 9, 10]. All factors can act simultaneously and their main cause is heat dissipation on the transitional contact resistance. Moreover, in the event of sparking or arcing, to these factors are added electro-erosion and emissions of the contact material in the arc discharge, welding and bridging, which increase wear rate.

With this in mind, it is possible to propose indirectly to determine the state of the friction pair surfaces and the quality of current collection on the basis of measuring and controlling the intensity of heat generation in the contact zone.

From the point of view of materials, several methods and approaches are used to increase the reliability of the operation of sliding electrical contacts and to increase their resource. Common to them is the use of contact materials with a thin transition layer, for example, the use of composite materials containing electrically conductive lubricants and having the property of self-lubrication.

At the moment, on the electric rolling stock of the railways of Ukraine, two main types of materials are used for making contact pads of pantograph runners - metal composite materials based on copper or iron and composite based on carbon (coke).

The advantages of contact pads made of materials of the first type include low electrical resistivity, high strength, relatively high intrinsic wear resistance. At the same time, their main drawbacks are high density, and, accordingly, an increased mass of the pantograph skid, which impairs its dynamic characteristics, relatively high wear intensity of the contact wire and high cost.

The advantages of contact inserts based on carbon include their low density, low wear rate of contact wire, low cost. The disadvantages are high electrical resistivity, low ductility, low wear resistance of the lining, especially with intensive current collection.

As a result, metal-based materials are used in Ukraine for the manufacture of contact pads for pantographs of current collectors of high-power DC electric locomotives. Carbon based contact inserts are used to make inserts used in direct and alternating current electric trains and alternating current electric locomotives.

On DC electric trains, carbon and carbon-copper inserts are used as current-collecting elements to reduce wear on the contact wire. Operating experience has shown that the wear rate of the copper contact wire (starting from a current of 20...30 A) increases significantly with the combined use of current collector plates and inserts based on iron and carbon. The mechanism of such incompatibility is associated with the fact that during the operation of carbon-graphite inserts the surface layer of the contact wire recrystallizes to a depth of 1 mm, and during the operation of metal-ceramic it is intensively heated [14].

In the case of simultaneous use of collector plates made of iron and copper composite materials, and inserts of carbon graphite, metal-ceramic works as an abrasive, which wears out intensively and wears the contact wire.

To a separate category, according to the combination of properties, it is necessary to attribute new materials, combining the advantages of the previous two types. Pads made of such materials are versatile and can be used on both direct and alternating current lines. An example of such a material is the “ROMANIT-UVLSh” fullerene-graphite material. During its production, a natural mineral containing up to 60% of fullerenes of carbon C_{60} is introduced into the material of the collector element. Due to the fact that the fullerenes of carbon C_{60} have a higher symmetry and the greatest stability this allowed us to create a material with improved electrical, tribological and mechanical properties. Joining to the fullerene carbon a metal-containing copper radical strengthened by chromium iron, tetravalent molybdenum compounds, ultradispersed diamonds reduces the affinity of this molecule with an electron, allowing you to get a new class of current-collecting composite lining pantographs with parameters that can change in wide limits. In this case, fullerene molecules play the role of the main chain [11].

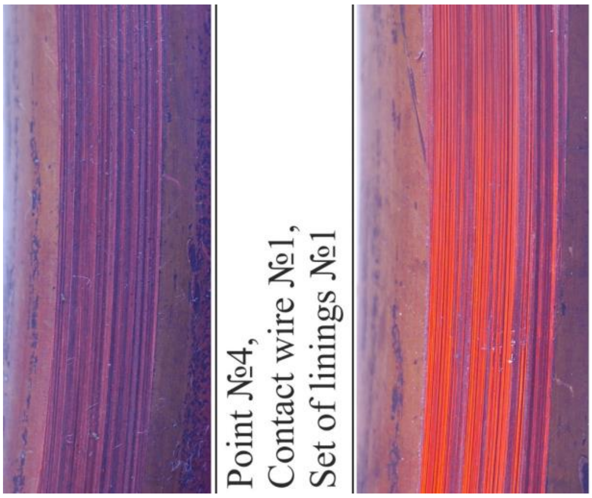
The addition of metal-containing copper radicals strengthened with chromium iron to fullerene carbon, tetravalent molybdenum compounds, and ultrafine diamonds forms chains that are called “the pearl string”. The formation of such chains provides a high electrical conductivity of the material and a very low coefficient of friction, and also firmly holds copper-clad graphite granules, which form a solid film of solid lubricant during friction on the contact surfaces.

The sectoral research laboratory “Reliability and unification of electrical equipment of rolling stock” of the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan conducted bench tests of wear resistance of contact pads of current collectors made of “ROMANIT-UVLSh” material and their effect on the contact wire wear. For this purpose, a special stand was used, in which the wear simulation is performed using a rotating disk, whereby the disk is made of material of a contact wire and a ring of a contact wire is rigidly fixed on it. In the course of the experiment, a pair of samples made of a contact pad is pressed against the disk with a fixed force; an electric current is passed through each sample. The following parameters are monitored: heating of the sample contact point with the contact wire; the amount of wear of the samples and the contact wire. The boundary values of these parameters and test conditions are governed by HOST 2584-86 and HOST 32680-2014 [12, 13].

Bench test conditions:

- current 300 A;
- linear speed in the sliding contact 4.83 m/s;
- experiment duration 50 min. (simulates 10000 passes);
- contact temperature limit should not exceed 95ºC;
- measuring the height of the contact wire after the experiment was carried out in two stages: stage 1 – without cleaning the surface of the contact wire; stage 2 – after cleaning the surface (used cloth soaked with alcohol).

The state of the surface of the contact wire before the start of the experiment can be estimated from the photo shown on fig. 2 a. According to the photo shown on fig. 2 b it is possible to assess the state of the surface of the contact wire after the



a) b)

Fig. 2. Photos of the surfaces of the contact wire: a) before the experiment; b) after the experiment (without cleaning the surface)

experiment, but without cleaning. In general, the surface of the contact wire has no damage and scoring, is evenly worn, and also has a specific color, which can be explained by the coating of the wire, during the experiment, with a protective conductive film. Even after intensive cleaning, the film is partially retained on the surface of the contact wire.

The maximum linear wear of contact patch samples was 0.039 mm and 0.021 mm, respectively, for the first and second samples. The surface is exemplary clean, has no damage and is covered with a layer of greasy lubricant.

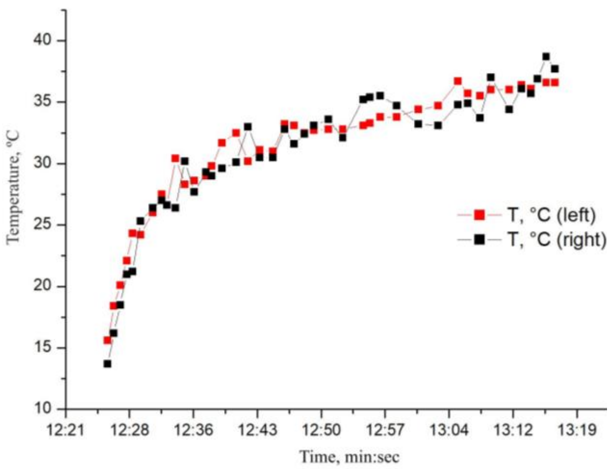


Fig. 3. Time variation of the sliding contact temperature

From table 1 it can be seen that the average wear value of the contact wire per 10000 passes was 35 microns (after cleaning the surface), which does not exceed the standard value of 40 microns [12]. The average thickness of the lubricant layer is 24 microns.

The limit temperature for the MF-100 type contact wire is 95 °C [13], during bench testing the temperature in the contact zone did not exceed 36...38 °C, which is significantly less than the normalized value. On the fig. 3. shows the curve of change in the contact temperature throughout the experiment.

RESULTS

The latest achievements of science and technology in the development of new types of materials for contact elements used in sliding high-current contacts create conditions for solving many current problems in electric transport, and also contribute to the further development of the industry as a whole.

The current collection pads considered in the work fully comply with the requirements for such products. The material "ROMANIT-ULShH" within the framework of bench tests showed minimal wear of both the lining itself and the contact wire. A slight heating of the contact zone allows us to hope for high energy performance in the course of operation of an electric rolling stock equipped with a slip-pad of a current collector made of this material.

The problem of reliable and economical operation of high-current sliding electrical contacts cannot be solved only by materials, construction or technology, but requires an integrated approach to oneself taking into account the actual operating conditions.

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