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THE USE OF INNOVATIVE CONTACT STRIP FOR PANTOGRAPHS OF ELECTRIC ROLLING STOCK. EXPERIENCE IN OPERATIONAL AND BENCH TESTS

Abstract: *Modern high-tech composite materials are widely used in various sectors of the economy, in particular, in railway transport. Among the areas of application of such innovative materials, the manufacturing of contact strips for pantographs of electric rolling stock should be mentioned. Innovation is primarily understood as the self-lubricating property of the working surface of the linings. The linings made of such materials differ from the traditional graphite (coal) ones by the increased content of metal additives, in particular copper, which limits the possibility of their use on electric rolling stock in the countries of the European Union. Regulatory restrictions on the content of copper (35% and 40%) are associated with possible damage to the contact wire, in the case of using overlays with a content of copper (metals) greater than these restrictions. On the railways of Ukraine (countries of the former USSR), there are also restrictions on the use of linings of different types according to the degree of wear of the contact wire, no more than 40 microns is allowed per 10 thousand passes of the locomotive pantograph along the contact wire. These standards are verified during operational and bench tests. The aim of the article is to present the types of tests and compare the obtained values with similar indicators in the case of using a traditional contact strip for pantographs of electric rolling stock. The results obtained confirm the possibility of using innovative linings on iron networks, since the wear of the contact wire during testing is much lower than that of the normative and knife than for traditional types of linings. In addition, during a set of tests, the fact of improving the quality of the working surface of the contact wire was established, which positively affects the extension of the service life of the contact wire.*
Keywords: sliding contact, electric locomotive pantograph, pantograph contact strip, contact wire wear, bench tests

1. Introduction

Railway transport plays a key role in the economy of an industrially developed country, since it provides a relatively low cost of transportation of various industrial cargo such as ore, metal products, products of chemical enterprises, and others. In railways, diesel and electric locomotives are massively used as traction rolling stock. Electric locomotives have higher energy and economic indicators, which is due to their ability to realize power, limited only by the capabilities of the centralized power system. The power of diesel locomotives is significantly limited by the capabilities of diesel engines and the generators of electrical energy driven by them, installed on board of these locomotives. Furthermore, the cost of electricity received from the centralized power system is obviously lower than the cost of electricity in the local power system of a locomotive. However, the use of electric traction requires significant investment in a traction power system, which consists of a traction substation and a traction contact network. On Ukrainian railways, direct current traction networks with a voltage of 3 kV and alternating current of an industrial frequency of 50 Hz with a voltage of 25 kV are used. When driving, electricity is transmitted to the electric locomotive power system through the sliding contact "pantograph contact strip-contact wire". The traditional pantograph contact strip is carbon-graphite, i.e., it is softer than the contact wire, which causes increased wear when driving. This is a deliberate action aimed at preserving the working surface of the overhead wire, since replacing the pantograph contact strip is much easier and cheaper than replacing the overhead wire. However, with an increase in travel speeds and an increase in power, carbon-graphite inserts began to undergo excessive wear, negatively affecting the reliability of the current collection process and the locomotive as a whole; electric locomotives need to be repaired more often, which has led to an increase in the cost of transportation. To solve the problem of increasing the reliability of the current collection unit, modern composite materials have found wide application. However, their implementation on electric rolling stock of railways requires a whole set of tests, one of which is the test to determine the wear of the contact wire. The standard value of the wear of the contact wire is 40 microns per 10 thousand passes of the pantograph (locomotive) along the section (fragment). These tests are carried out in two independent stages - bench tests and operational tests. In the presented article, the results of operational and bench tests of an innovative contact strip for a pantograph are collected and systematized, hereinafter we will call this contact strip "innovative". The test results are carried out in comparison with the indicators of the contact strips currently used on the electric rolling stock, which will be further identified as "traditional". Innovation means, first of all, the property of self-lubrication of the working surface of the contact strip. A part of this lubricant will naturally be applied to the working surface of the contact wire, thus creating a protective conductive layer.

From the point of view of the regulatory requirements binding in the EU countries, the innovative insert differs from the traditional one in the increased content of metal additives, in particular copper, up to 70%, which limits the possibility of their use on electric rolling stock in the EU countries. Regulatory restrictions on the copper content (35% and 40%) are associated with the possible damage to the contact wire. Therefore, it is believed that the results obtained during bench and operational tests can serve as a basis for raising the question of the possibility of making changes to the regulatory framework for innovative inserts on the railways of the EU countries.

2. Analysis of literature sources

It is known that the power sliding contact, through which electrical energy is transmitted on board of the vehicle, is a tribosystem through which the electric current flows. The contacts are subjected to friction forces, which cause their mechanical wear, heating and increase the flow of chemical reactions on the friction surfaces [2]. The flow of significant currents through the power sliding contact leads to EDM processes in them, and they are completely identical to similar processes in switching contacts [4, 16]. Electrical and mechanical processes affect each other, which can both increase the intensity of wear and weaken it, i.e., there is a synergistic effect [4, 9].

Increasing the service life of the sliding contact can be achieved by reducing the intensity of wear by correct selection of the elements of the contact pair in terms of their tribological compatibility and ability to provide high-quality current collection [12].

Recent advances in 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, as well as contribute to the further development of the industry as a whole. On the Ukrainian railways, copper tires with natural graphite embedded in the grooves are most often used as contact inserts of the pantograph; copper graphite inserts; carbon inserts type A, B and 0, as well as recently composite copper-based with widely developed self-lubricating properties. The latter are of the greatest interest because they have significantly improved electrical and mechanical properties [15], and in fact, combine the advantages of metal composites and carbon materials.

In [18] on the basis of long-term operational studies it was concluded that the universal contact strip should combine high physical and mechanical characteristics with high arc resistance, density and low electrical resistance.

Hoffmann [8] proposed a design of a carbon contact strip with porosity creating high-density graphite, brands SK85ACu, SK01ACu and others. After the next impregnation with copper, continuous electrically conductive bridges (channels) are formed, saturation with copper of these veins in the volume of 20-30% of graphite mass provides natural passage of current from the point of contact of the contact strip with the contact wire to the metal base.

In the production of contact inserts from the material described in [15], a natural mineral containing up to 60% of C60 carbon fullerenes is introduced into the chemical composition. Together with carbon fullerene metal-containing copper radicals reinforced with chromium cast iron compounds of tetravalent molybdenum, ultrafine diamonds form chains called "pearl thread". The formation of such chains provides high electrical conductivity of the material and a low coefficient of friction, and also helps to retain copper-plated graphite granules on the contact surfaces.

To check the compliance of the contact inserts of the pantograph with the requirements of the standard DSTU GOST 32680: 2016 "Current-removing contact elements of current collectors of electric rolling stock. General technical conditions" [3], acceptance and standard tests should be done. The program of such tests includes checks of run of contact inserts and wear of a contact wire. The range of contact strips to the limit wear is determined by the results of operational tests. Contact strips are considered to have passed the test and must have a calculated replacement forecast for the maximum wear not less than: for light type current collectors $60 \cdot 10^3$ km and more; for current collectors of heavy type $25 \cdot 10^3$ km and more point 5.1.5 DSTU GOST 32680: 2016 [3]. Checking the level of wearing of contact wire was conducted on the stand. The technique of such laboratory tests puts forward the following requirements to the stand: the segment of a contact wire of MF-100 is fixed in the form of the closed curve on the rotating device providing linear speed of any point of a wire not less than 16 m/s. on it inserts. Two identical fragments of the contact insert are installed on the stand opposite to each other; two identical fragments of the contact insert which are pressed to the contact wire by force (40 ± 8) N. The amount of wear of the contact wire is considered acceptable if after 500 thousand revolutions of the rotating device it does not exceed 2 mm 8.3.13 DSTU GOST 32680: 2016 [3]. The branch research laboratory (GNDL) "Reliability and unification of electrical equipment of rolling stock" of the Dnipro National University of Railway Transport named after Academician V. Lazaryan is equipped with a stand to determine the amount of wear of the contact wire [17]. Such stands are used by many laboratories around the world in studying the properties of not only sliding contacts, but detachable contacts, and contacts of electrical devices [1, 6, 20].

The test program provides for bench and operational tests of the tribological system contact insert - contact wire.

The obtained results of operational tests on the lines must be adjusted with the results of bench tests. In practice, differences are inevitable, but this may be due to the influence of the design of pantographs and climatic factors that occur in operation.

In [8] the results of operational tests of contact inserts based on high-density graphite are given. Thus, on the routes Paris-Toulouse and Paris-Tarbes with speeds over 140 km/ h, the surface condition of the contact insert and contact wire was satisfactory. The mileage of the set of inserts was almost twice as long as the mileage of current collectors of high-speed TGV trains, which were equipped with metal contact inserts. However, the observations revealed wear peaks corresponding to the winter months, when the rate of wear increased almost threefold [8], mainly due to icing of the catenary.

The analysis of the results of operational tests of contact inserts made of material [15] at the sites of the regional branch "Lviv Railway" PJSC "Ukrzaliznytsia" showed that the use of composite materials based on copper with advanced self-lubricating properties reduces annual costs for contact inserts by an average of 3.09 times compared to traditional inserts [11]. There is also a satisfactory condition of the contact wire and the absence of peak wear due to climatic factors.

In [1, 19] it is shown that the contact wire and the contact strip of the pantograph wear more intensively when current flows through the power contact, the vehicle moves at high speed, and when the power contact is affected by adverse weather factors (ice, water, high ambient temperatures, environment, etc.).

Studies [14] demonstrate the results of mathematical modeling of contact pair wear taking into account the ambient temperature. The analysis shows that the wear is largely determined by the temperature of the friction bodies, which affects the hardness of the contact pair elements and the actual contact area. The dominant role of the electrical component of wear in raising the temperature of the friction pair is shown in [21].

The material of the article [13] presents a model for the analysis of the contact pair "contact wire - carbon contact strip" by the method of finite elements of its stress-strain state, taking into account the temperature factor. The simulation results obtained in the ANSYS Mechanical and ANSYS / LS-DYNA environments provide a deeper understanding of the mechanisms of temperature distribution in contact and can be used to improve the pantograph performance.

The results of both operational and bench tests are probabilistic, so they must be processed using the methods of mathematical statistics and probability theory. Operational tests and, to a lesser extent, the stand requires significant financial and time costs, so the obtained statistics on the results of their conduct can be used as a basis for mathematical models of sliding contact formed by the contact wire and various contact inserts. One of the main tasks of studying the operation of power sliding contact of electric rolling stock is the ability to predict the intensity of wear of both the contact wire and the contact inserts of the pantograph. Recently, much attention has been paid to this, which only proves the urgency of the problem [5, 7, 10].

3. Results of operational tests

Operational tests were carried out on the Lviv railway in two stages - the first at 3 kV DC sections, and the second at 25 kV AC sections.

The first stage - DC tests were carried out initially by railway workers and showed the following results (reported at the meeting on May 27, 2016): there were 925 passes of rolling stock on the experimental section "Gorodok - Zatoka - Mshana"; the share of electric locomotives with innovative pantograph linings was 9%; the average wear of the contact wire ranged from 2.9 to 3.5 sq. mm in different anchor sections in even and odd directions. The working group pointed out that the share of electric locomotives with innovative linings is very small. Therefore, it was decided to conduct repeated tests on the same section with the involvement of specialists from the Dnipro National University of Railway Transport named after Academician V. Lazaryan. These tests were carried out from June 14, 2016 to July 26, 2016 at the "Gorodok - Zatoka - Mshana" section daily recording the number of passes of electric locomotives and electric trains on the experimental section. However, not all electric rolling stock, which was operated at the experimental site, was equipped with innovative linings. The analysis of the daily dynamics of the number of passes of electric rolling stock (by the number of pantographs) in the experimental section shown in fig. 1 shows that, on average, the share of pantographs with innovative linings at the end of the test period averages 76.25%, and in the initial period this share was 21.14%.

Measurements of the height of the contact wire were carried out in four sections, according to standard methods, using a micrometer. During the operational tests, each micrometer reading was recorded using photographic equipment with time and location (GPS) (fig. 2).

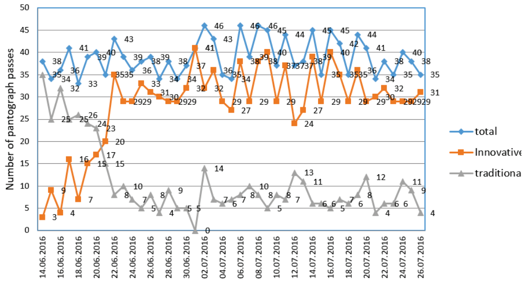

Fig. 1. Daily dynamics of electric rolling stock passes (by the number of pantographs) at the experimental site

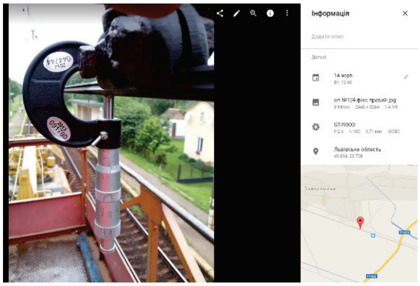

Fig. 2. Screenshot of a photo with measurements of the height of the contact wire

The wear of the overhead wire during the test period was determined as the difference between the heights of the overhead wire h on the anchor sections following the measurement data on June 16 and July 26, i.e. $\Delta = h_{16.06}-h_{26.07}$. The measurement results for each anchor section are of a probabilistic nature and were calculated as the arithmetic mean of the height of the contact wire. Two of these histograms of the obtained values are shown in figs. 3 and 4.

Measurements of contact wire wear were carried out at the following points: Gorodok-Zatoka (even path) - contact wire supports №№ 2, 4, 6, 8, 10; "Zatoka-Mshana" (even path) - contact wire supports №№ 120, 122, 124, 126; Mshana-Zatoka (odd path) - contact wire supports №№ 133, 131, 129, 127; "Zatoka-Gorodok" (odd path) - contact wire supports №№ 11, 9, 7, 5, 3, 1.

It is useless to determine the law of distribution of the investigated value of wear of a contact wire as in the end only numerical characteristics describing the most essential characteristics of this distribution are required. Such a characteristic, in our case, can be a mathematical expectation.

In the even direction, 1547 passes of the electric rolling stock were recorded, while the wear of the contact wire was 0.09 sq. mm, which, in terms of the reference 925 passes, will give a wear value (0.09 / 1547) 925 = 0.054 sq. mm. Thus, an increase in the share of rolling stock with innovative contact strips by 76.25 / 9 = 8.47 times made it possible to reduce the wear of the contact wire in an even direction by 3.5 / 0.054 = 64.8 times.

In the odd direction, the number of passes is 1586, while the wear is 0.2 sq. mm, which in terms of reference 925 passes will be (0.2 / 1586) / 925 = 0.12 sq. mm. Thus, an increase in the share of rolling stock with innovative linings by 76.25 / 9 = 8.47 times made it possible to reduce the wear of the contact wire in the odd direction by 3.5 / 0.12 = 29.2 times.

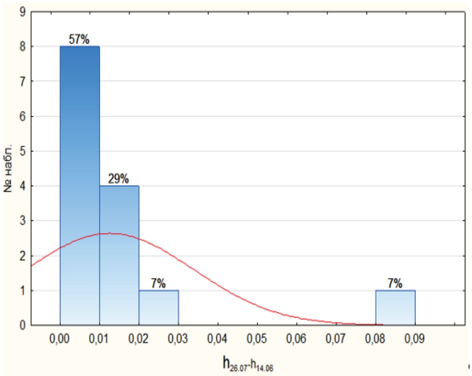

Fig. 3. The results of processing the values of the difference in heights of the left contact wire in the odd direction

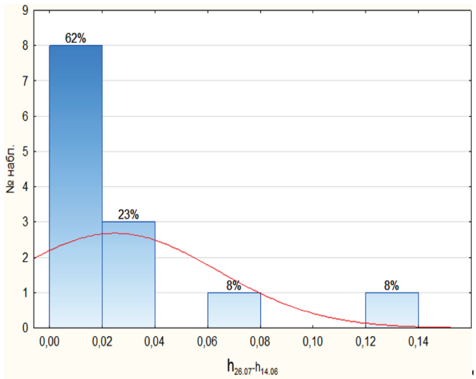

Fig. 4. The results of processing the values of the difference in heights of the left contact wire in the even direction

It should be mentioned that the share of innovative contact strips was 76.25%, with an increase in this share, the decrease in wear would be even greater. This result is due to the effect of lubricating the working surface of the contact wire with a conductive lubricant included in the innovative contact strip (self-lubricating effect). This is very clearly demonstrated by photographs of the working surface of the contact wire taken on June 14 and July 26 (figs. 5 and 6). The photographs (fig. 5), taken on June 14, 2016, clearly show the surface of the contact wire, formed as a result of operation on the “Gorodok-Zatoka-Mshana” section with the traditional pantograph pads used. As can be observed in the photographs, the surface of the contact wire is very worn, very rough, torn, with deep seizures, grooves and cavities in copper.

The photographs taken on July 26, 2016 clearly show the surface of the contact wire in the Gorodok-Zatoka-Mshana section, formed as a result of the operation of innovative pantograph inserts in the amount of 76.25% of the total number of passes of all pantograph skid linings in the period from 06/14/2016 to 26/07/2016. These photographs reveal that the surface of the contact wire is smooth, greasy, shiny, covered with a protective conductive film. Roughness, scuffs, abrasions, grooves and cavities are filled with carbon globules that protect the contact wire from wear and as a result, the worn out and torn surface of the contact has been restored. This phenomenon is explained by the fact that the main component of the innovative contact strip material is a multilayer carbon globule with a size of about 10 nm, the structure of which is very active in redox reactions, has sorption and catalytic properties and has the highest symmetry and high stability.

Fig. 5. The working surface of the contact wire at one of the control points, as of June 14, 2016

Fig. 6. The working surface of the contact wire at one of the control points, as of July 26, 2016

The second stage included operational tests in areas that are electrified by alternating current. Tests were conducted from October 11, 2016 to March 30, 2017 at the experimental section "Ternopil - Hlybochok Velykyi - Ozerna" of the Lviv Railway.

Measurements of wear of a contact wire were carried out in the following points: "Ternopil - Hlybochok Velykyi" (odd way) - support of a contact wire №№ 51, 49, 47, 45, 43, 41; "Ternopil - Hlybochok Velykyi" (even path) - contact wire supports №№ 156, 158, 160, 162, 164, 166, 168; "Hlybochok Velykyi - Ozerna" (odd way) - contact wire supports №№ 343, 345, 347, 349, 351, 353, 355, 357; "Hlybochok Velykyi - Ozerna" (even path) - contact wire supports №№ 342, 344, 346, 348, 350, 352, 354, 356.

During the measurements, the condition of the surface of the contact wire was photographed in order to verify the fact of applying a protective conductive layer on the working surface of the contact wire. Comparisons of the condition of the working surface of the contact wire as of 11.10.2016 and as of 30.03.2017 confirm this fact (figs. 7 and 8). The analysis of the presented photographic materials allows us to determine that in the experimental areas the working surface of the contact wire is uniform and has a stable protective film. The working surface of the contact wire is uniform, the grooves are "tightened" with lubricants. Graphitization of the surface is observed.

Fig. 7. The working surface of the contact wire in one of the control points, as of October 11, 2016

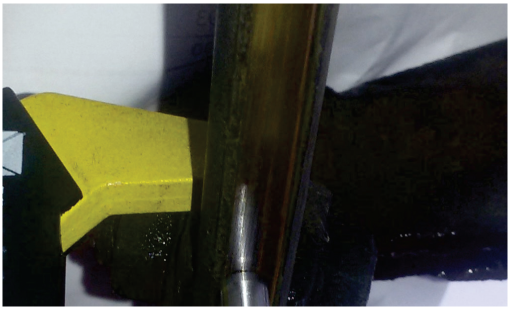

Fig. 8. The working surface of the contact wire in one of the control points, as of March 30, 2017

During the testing period, 3148 passes of electric rolling stock in the odd direction and 3224 in the even direction were recorded at the experimental site, while the share of electric locomotives and electric trains with innovative linings was 32.5% and 31.0%, respectively. During the test period, the wear of the contact wire was not detected, but the approximate thickness of the protective film on the working surface of the contact wire was recorded. The thickness of this protective film is approximately 0.01 mm, and it can be assumed that with increasing the share of electric rolling stock with innovative contact strip of pantographs - this value will also increase.

4. Results of bench tests

The purpose of bench tests is to determine the wear of the contact wire, and compare this value with the standard of DSTU GOST 32680: 2014 [3, 15]. The wear should not exceed 40 μm per 10,000 passes of the test bench disc. The general view of the stand, which is installed in the specialized laboratory of the Dnipro National University of Railway Transport named after Academician V. Lazaryan, is presented in fig. 9.

The initial test conditions were as follows. The height of the cross section of each sample of rings made of contact wire MF-100 was measured at 6 points, evenly spaced around the circle with a micrometer. The value of direct current 300 A in the circuit is determined from the calculation of the geometric dimensions of the test sample taking into account the maximum allowable, provided by regulatory and technical documentation, in accordance with paragraph 8.3.13.2 DSTU GOST 32680: 2014 [3, 15]. It was assured the pressure at the place of current collection with the corresponding force of 40 ± 8 N and tests of wearing of a contact wire on stand at a speed of 205 rpm.

Fig. 9. Stand for testing the wear of the contact wire

An innovative pantograph contact strip and several types of traditional ones were tested at the stand, followed by a comparison of the contact wire wear indicators for all these samples. An innovative sample was adopted as a reference, which was tested first.

Figure 10 shows a general view of a fragment of the innovative contact strip (sample 1), and fig. 11 shows a photo of the surface of the contact wire after testing.

Fig. 10. The general view of a fragment of the innovative contact strip (sample 1)

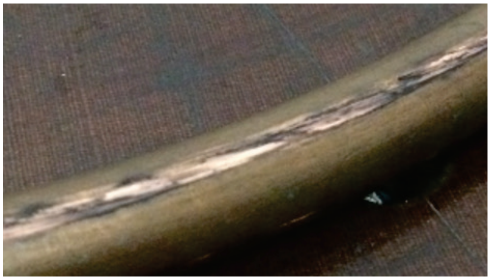

Fig. 11. The photo of the surface of the contact wire after testing of the innovative contact strip (sample 1)

The surface of the contact wire after testing is even not damaged. The average wear of the contact wire when simulating 10 thousand passes of the pantograph was 10 μm, which does not exceed the standard value of 40 μm.

Figure 12 shows a general view of a fragment of the traditional contact strip (sample 3), and fig. 13 shows a photo of the surface of the contact wire after testing.

Fig. 12. The general view of a fragment of the traditional contact strip (sample 3)

Fig. 13. The photo of the surface of the contact wire after testing of the traditional contact strip (sample 3)

The surface of the contact wire after testing is even not damaged. The average wear of the contact wire when simulating 10 thousand passes of the pantograph was 27 μm, which does not exceed the standard value of 40 μm.

Figure 14 shows a general view of a fragment of the traditional contact strip (sample 8), and fig. 15 shows a photo of the surface of the contact wire after testing.

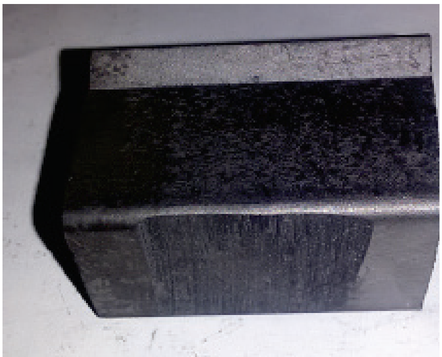

Fig. 14. The general view of a fragment of the traditional contact strip (sample 8)

Fig. 15. The photo of the surface of the contact wire after testing of the traditional contact strip (sample 8)

The surface of the contact wire after testing has damage and burrs. The average wear of the contact wire when simulating 10 thousand passes of the pantograph was 32 μm, which does not exceed the standard value of 40 μm.

Figure 16 shows a general view of a fragment of the traditional contact strip (sample 9), and fig. 17 shows a photo of the surface of the contact wire after testing.

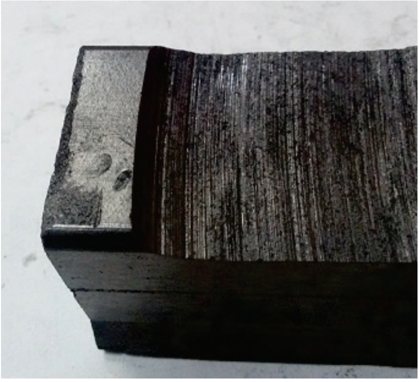

Fig. 16. The general view of a fragment of the traditional contact strip (sample 9)

Fig. 17. The photo of the surface of the contact wire after testing of the traditional contact strip (sample 9)

The surface of the contact wire after testing has damage and burrs. The average wear of the contact wire when simulating 10 thousand passes of the pantograph was 59 μm, which exceeds the standard value of 40 μm.

5. Conclusion

The results of the conducted operational and bench tests of innovative pantograph contact strips for electric rolling stock confirm their compliance with the current standards for the wear of the contact wire, and also prove their positive effect on the state of the working surface of the contact wire. It is demonstrated that the wear of the contact wire in the direct current sections is reduced by 30-60 times, with the introduction of innovative pantograph contact strips on the electric rolling stock. It has been proved that during the operation of innovative linings, on the alternating current sections, a protective conductive film with a thickness of approximately 10 microns is applied on the working surface of the contact wire, which protects the contact wire from wear. Bench tests have shown that the average wear of the contact wire is 10 microns per 10 thousand passes of the test bench disk, which is 4 times less than the standard value. In the course of the set of tests that were carried out, no negative impact on the contact wire of innovative contact strips was revealed. These linings can be permitted for operation on the railway network electrified with direct and alternating current.

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