Проведено дослідження взаємодії контактних елементів пантографів електричного транспорту, що експлуатується на ділянках постійного та змінного струму залізниць. На відміну від відомих методик стендових випробувань, досліджено механізм струмознімання і зносостійкості на новій випробувальній установці у мінімально вузькій зоні ковзного контакту, що імітує явище "пропилу" пантографа. Дана установка може бути використана як в заводських умовах при виготовленні нових контактних елементів, так і в лабораторних при дослідженнях зносостійкості.

Експериментальними дослідженнями підтверджено, що інтенсивність зносу контактних елементів струмоприймачів залежить від струмового навантаження зони контакту, величини контактного натиску, площі контактуючої поверхні та швидкості руху. Практично доведено можливість збереження надійного контактного з'єднання у ковзному контакті в екстремальних режимах експлуатації при використанні надійного контактного матеріалу накладок струмоприймача.

Запропоновано використання композиції порошків БрЗГ на основі бронзи, заліза і графіту для виготовлення контактних елементів струмоприймачів, які можуть забезпечувати надійний контакт при взаємодії з контактним дротом. Використання нових і якісних контактних матеріалів впливає на трибологію та стабільність взаємодії контактних пластин та контактного дроту.

Завдяки проведеним дослідженням знайдено можливість виготовлення надійного контактного елемента БрЗГ, який збільшить довговічність взаємодії контактної пари "струмоприймач електричного транспорту – контактна мережа".

Практична цінність досліджень доведена ефективністю використання нового контактного матеріалу БрЗГ на мережі залізничного електричного транспорту, на тролейбусах і трамваях.

Таким чином, є підстави стверджувати про можливість продовження терміну експлуатації контактної пари "накладка струмоприймача електричного транспорту – контактна мережа" шляхом використання нового контактного матеріалу БрЗГ

Ключові слова: накладки пантографа, вставки струмоприймача, контактний матеріал, знос контактів, контактна пластина, електричний транспорт

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COMPARATIVE TESTS OF CONTACT ELEMENTS AT CURRENT COLLECTORS IN ORDER TO COMPREHENSIVELY ASSESS THEIR OPERATIONAL PERFORMANCE

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1. Introduction

The main problem for electric transport at railroads operated by direct or alternating current is the wear of contact elements at current collectors. Operational reliability of the contact pair "contact element in a pantograph – contact wire" depends on the quality of a material that both elements are made from. It is affected by the character of wear, the magnitude of operational wear, mechanical damage, electromechanical processes in the contact area, climatic conditions, a train driving mode, as well as the tribotechnical properties of contact materials.

There is not a doubt that the requirements should be mostly met by the contact wire, which is mainly made of copper [1]. Copper fitting contact wires no longer meet modern strict requirements for the operation of heavy freight trains, or high-speed passenger trains.

Contact materials for current collectors at electric rolling stock must enable high-quality transmission of electrical current both to power electrical circuits and to provide for the uninterrupted power supply to equipment whose work ensures the functioning of the entire rolling stock, as well as traffic safety.

Currently, there is no a contact material, which would fully meet the requirements of OSZ Instruction P674/1 [2] regarding the minimum wear of the contact wire and the contact plates themselves, as well as low specific resistance of the sliding contact pair.

It is a relevant task to develop a new contact material, which could satisfy the needs of both the mainline and industrial transport for all motion speeds and urban electric transport.

This paper examines the possibility to use the pantographs' pads made from the new contact material BrIG, based on bronze, iron, and graphite, in line with the results from comparative bench tests involving the pads made by different manufacturers. Estimation of current collection and wear of the sliding contact is performed over a minimally narrow contact zone at different currents and different motion speeds.

2. Literature review and problem statement

In accordance with the Rules for maintenance and repair, electric rolling stock operated by alternative current must use coal inserts as the contact elements in current collectors [3–5]. Some locomotive and wagon depots utilized contact inserts based on copper or graphite, which have a greater resource than the conventional ones.

In order to improve reliability of the contact "coal insert in a current collector at electric rolling stock – contact suspension", paper [6] applies laser strengthening of the contact wire and the coal inserts themselves. The paper does not provide enough information on the possible performance of such a contact wire at sections with copper inserts. Another unresolved issue relates to the way the contact wire and inserts would work on freight and passenger trains at different currents.

When studying the quality of fabrication of current collection inserts made by different manufacturers using field samples [7], the authors narrowed the range of hardness for coal inserts and devised a procedure for sorting coal inserts based on hardness; a mismatch was established between current collection inserts and existing regulatory requirements. The inserts have been found to demonstrate the structural heterogeneity of the material with fluctuations in the insert density lengthwise. The relationship between the hardness of inserts and specific electric resistance was established. However, it is not known whether at least in a single locomotive depot hardness is checked, or the installation of all coal inserts is performed in accordance with the proposed procedure; given the hundreds of inserts used daily, it is physically impossible.

One of the drawbacks of graphite current-collecting elements is the lack of the physical-chemical interaction between constituents of the material, which is the cause of high specific resistivity and low wear resistance [8]. Bench tests of sliding contacts made from press-powder based on natural graphite and artificial graphite (sample 1), and based on natural graphite and pyrolytic carbon (sample 2), showed that the average specific wear of the suggested inserts is less by 1.3...1.9 times than that for standard graphite-based. In the presence of water in a contact zone, the contact resistance of the examined inserts is 1.1...1.4 times lower in comparison with standard ones. The described bench study is performed only for the inserts for trolley bus, which have their own specificity.

It is implied that electric rolling stock operated by direct current [9] should use as a pad at the current collector's skids a copper bus of 6×30 mm [10], which rapidly wears out the contact wire and wears out itself. It is permitted [11] to apply the copper-graphite inserts, or metallic-ceramic pads, for example, iron-and-copper-based, impregnated with the lead-tin alloy VZh3p, which require constant lubrication with the graphite grease SGS whose efficiency is not high enough [12]. Taking into consideration the operational deficiencies, the requirements of environmental safety, significant wear of the contact wire, as well as other factors, these plates are forbidden to use.

Study [13] shows that the simultaneous operation of sliding contact elements made from various materials is accompanied by the destruction of the old structures, and the emergence of new secondary structures, which leads to intense wear because they are constantly in the process of adjustment. Regulations in Ukraine and in the European Union forbid the application of different contact materials at the same section.

Contact insert must meet the criteria for a minimum wear of the contact wire while ensuring a reliable current collection, as well as have the maximum possible mileage between repairs. That is, a material of the insert must have high physical-mechanical and anti-frictional characteristics, low specific and transient resistivity, high electric-erosion resistance, which sometimes is incompatible, or difficult to implement [14]. It is especially difficult to combine these properties under conditions of urban electric transport.

The disadvantage of the Slovakian copper-graphite contact plates MG-487 is a low coefficient of friction and insufficient arc resistance at current collection. Seizing of contacting surfaces leads to increased wear of the contact wire and cuts the contact plates.

Similar shortcomings were observed in the continuous long copper contact plate with graphite inserts NMG-1200, produced by NTC "Reaktivelektron" (Donetsk, Ukraine). Their non-through openings were filled with graphite to the thickness of a working layer, which served as a regular graphite oil. It was not possible to improve durability and to reduce wear of the contact wire.

At present, the DC locomotives use the copper-based contact plates PKD-4, made by TOV "Inter–Contact–Prior" (Kyiv, Ukraine), which have a greater resource of exploitation than NMG-1200. However, the contact plates PKD-4 are also subject to electric seizing, pulling copper from the contact wire, burning and melting. One of the advantages over contact plates made by other manufacturers is the presence of embedded brass screws. Sometimes it becomes a disadvantage of this plate when a screw is detached from the plate, or breaks when using a screwdriver. Another advantage claimed by the manufacturer is a possibility to utilize these contact pads without an additional supply of grease to the contact zone. However, as it turned out during regular operation, some serviced sections require the lubrication in a contact zone.

The insert PKD-4-2-T from the same manufacturer was tested at tram cars [15]. The experiment involved the inserts based not on the strengthened copper, but on the disperse-strengthened copper (DZM), obtained using the technology of pressing with subsequent sintering, and based on DZM, obtained via hot punching. The pantograph inserts PKD-4-2-T demonstrated better performance and greater resource than the inserts based on aluminum AD31T.

The current-collecting inserts made from fullerene-carbon material "Romanit-UVLSh" [16] were examined at the sections operated by direct and alternating current. The insert has a steel substrate made of low-carbon steel, with a thickness of 2 mm, and a working layer with a thickness of 7 mm. Operation should not require additional lubrication, because the ready-to-use pads must be exposed to the vacuum impregnation with a lubricant according to the technological process at the manufacturing enterprise.

The quality of current collection, which depends on reliability of the contact between a current collector and the contact wire was examined in [17]. It is proposed to diagnose the results of poor interaction based on the overheating of a pantograph's pad and the action of an electric arc. However, this is a consequence of the operation, rather than a prediction of failure of the contact element.

The wear processes in a contact material at high sliding speed under the action of electric current, and without it, were investigated in [18]. The paper confirmed the effects of current and speed on the tribology of the tested material. However, currents in the experiments were relatively small, making it impossible to compare work of the contact pair under actual conditions.

The dependence of the electric arc resistance in a contact between the contact plate and contact wire, and the influence of arc on the wear mechanism of a contact pair was described in [19]. It was confirmed that enhancing the normal strength of pressing can suppress the arc charge and reduce wear of the contact plate. However, no data were given for low motion speeds at large currents, which does not provide full information in order to assess work of the contact elements at freight locomotives.

Paper [20] suggested predicting the wear of a contact plate under laboratory tests, which makes it possible to compare different materials and to establish a dependence on basic parameters such as the speed of sliding, contact strength, and the magnitude of current. The paper considers the dependence of resistance of electrical contact on the contact force between each contact strip from a pantograph and the contact wire. In order to control the process of wear, it is recommended to change the pull of the contact wire. No information is given regarding the use of different contact materials.

The effect of electric current, pressure strength, and motion speed on the friction and wear-resistant properties of a pure coal strip is explored in [21] at a test bench. The paper considers the influence of arc erosion, abrasive wear, and wear resistance on the wear of coal insert. It is shown that wear depends on the presence of current in the contact area. However, similar studies were not carried out for other materials, or no appropriate information is given.

Paper [22] investigated the coal insert only, as well as dependences of the coefficient of friction and wear on electric current. A similar study was conducted earlier [23] at high-speed friction. The main established wear components were the abrasive wear and arc erosion at the electric process of frictional sliding. No other materials, except for the coal insert, were covered.

The scientific literature shows [6–8, 15–23] that each researcher follows an individual path when tackling the problem of wear in the contact pair "a current collector's pad – the contact wire". Some are trying to improve the coal insert, while others address the issue by adjusting the pull of the contact wire. Attempts to industrially manufacture a universal reliable contact plate for direct and alternating current for all modes of transport have not yielded positive results up to now. This unresolved issue allows us to argue about the prospects of using powdered composite materials, as well as the relevance of studying a new contact material.

As regards the strong-current sliding contacts, it is better to use, rather than the artificial, natural graphite, which simultaneously performs the antifriction functions. For copper and copper-graphite contact elements, it is necessary to use the cleanest possible copper because impurities lower its conductivity.

When manufacturing and implementing the new contact element, it is expedient to conduct a comprehensive study, starting at raw materials that a contact element is made of, and all the way to analyzing the contact surface after wear.

The key factors both to the manufacturer and operation specialist are the findings by boards that conduct laboratory and operational tests.

3. The aim and objectives of the study

The aim of this work is to assess comprehensively the operational quality of contact elements at current collectors employed by electric transport.

To accomplish the aim, the following tasks have been set:

– to conduct a study into the physical, tribotechnical, and operational properties of current collectors' pads made from known contact materials and from a new promising material;

– to conduct comprehensive comparative laboratory and bench tests of pads made from the new material BrIG with known contact materials and to confirm the results obtained under conditions of actual operation;

– to quantify the technological and operational indicators for parametrical reliability of pads made from different materials based on the criterion of their wear;

– if the results of comprehensive tests prove positive, to implement the results of the development of the model range of pads BrIG at locomotive, wagon, trolleybus, and tram depots.

4. Materials and methods to study the influence of properties of contact materials on wear resistance of the contact elements at current collectors employed by electric transport

4. 1. Materials and equipment used in the study

In order to provide complete information, we performed analysis of operational conditions and compared basic characteristics of contact elements from current collectors used by electric transport, provided by manufacturers. In the comparative study we analyzed the most common contact elements:

– coal contact inserts for pantographs, type "A";

– coal contact inserts for pantographs, type "B";

– trolley bus inserts, type "B";

– carbon inserts for tram skids;

– pantograph copper for current collectors (copper bus 6×80);

– metallic-ceramic plates VZh3p;

– copper contact plates with graphite inserts NMG-1200;

– copper-graphite contact plates MG-487;

– contact plates, copper-based, PKD-4-2;

– current-collecting inserts made from fullerene-carbon material "Romanit-UVLSh";

– contact plates BrIG.

Basic requirements to the monitored parameters for current collectors are summarized in Rules for repair of the corresponding type of electric rolling stock. They are regulated by Technical requirements to current collectors at electric rolling stock P668 [24] and by GOST 32204-2013 [25]. Basic requirements to contact elements at current collectors and to their testing are given by GOST 32680-2014 [26] and by regulations of the European Union EN 50318:2002 [27].

Materials that the electrical contacts are made of must have, at high stability of transient resistance in the closed state of contacts, a good thermal conductivity and electrical conductivity. Contact surfaces of the material must have a high resistance to oxidation and electrical erosion in the state of closing and opening the contacts, low susceptibility to welding with return contacts. Paper [28] proposed meeting these strict and conflicting requirements partially by constructing composite materials based on graphite with the addition, in different proportions, of copper, or other fillers.

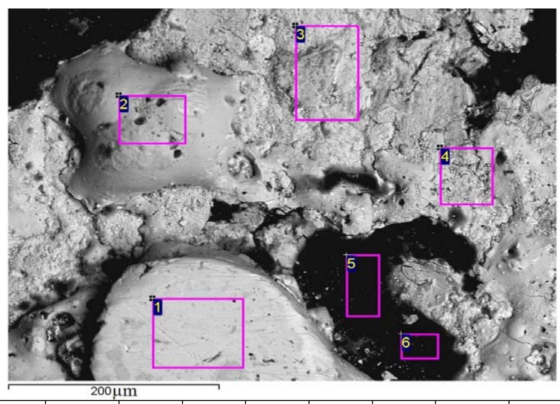
The base of a composition that we selected for the manufacture of a promising antifriction strong-current sliding contact element for the current-collecting element in a current collector used by electric rolling stock was bronze, iron powder, and natural graphite, which is why this material is termed BrIG [29].

In the course of design and research into the contact element BrIG, we experimentally determined the optimum content of natural graphite in the composition, at which the antifriction properties in the contact zone are provided, while maintaining the physical and mechanical properties of the contact element. An increase in the current of load at low speeds due to heating by the current strength, or at high speeds and small currents due to the friction forces, leads to the formation of a graphitized gloss at the surface of the contact element BrIG. That simultaneously "moistens" a contact zone and lubricates the contact pair "a current collector's pad the contact wire" [30].

The proposed composition allowed the technical fabrication of a material, which, without the use of external lubrication, ensures a wear reduction in the contact wire and current-collecting element by reducing a friction coefficient while maintaining the required mechanical and electrical-physical properties.

We performed the electron-microscopic and micro-X-ray spectral analyses using the raster electron microscope JSM-64901LV (Japan) equipped with the energy-dispersive spectrometer INCA Penta FETx3 (OXFORD Instruments). The plan of our study involves comprehensive macro-structural, micro-X-ray spectral, and micro-structural analyses for samples from each series of contact pads before and after operational tests. We examine the characteristics and structure of all pads; and identify the phase and structural components in the examined samples, as well as the volumetric percentage of components and structural homogeneity of materials.

In order to define the best sample of a material for pads to operate at a constant electric current, we employed contact plates made by different manufacturers. An example of study into the distribution of chemical elements in the structure of a pad composite material for the pantograph PKD-4 made by TOV "Inter–Contact–Prior" (Kyiv, Ukraine), which passed the test at Lviv railroad, is shown in Fig. 1 [32].



spectrum	C	O	Si	S	Ca	Cr	Mn	Fe	Cu	Mo	Pb
1	4.93	2.02	0.15	0.04	0	0	0.13	1.04	91.22	0	0.57
2	9.64	12.66	0.03	0	0.43	0.16	0	9.18	66.57	0.34	1.01
3	7.8	10.17	0.04	0.03	0.07	0.08	0	17.24	63.47	0	1.24
4	11.5	9.94	0.06	0.06	0.2	0.14	0.08	13.48	61.93	0.26	2.2
5	91.24	4.48	0.04	0.39	0.19	0.04	0	0.76	2.96	0	0.62
6	93.14	4.09	0.01	0.04	0.25	0	0	0.34	2.35	0	0.16

Fig. 1. Microstructure and chemical composition of the sample of a material for the insert made by TOV "Inter –Contac –Prior ", Kiev, Ukraine, which passed the test at Lviv railroad

For a fractographic study, we used the samples of broken inserts from pantographs, formed during operational testing, based on the criterion for detecting an initial crack and the structural components that initiate it.

For a qualitative analysis into the content of chemical elements in the samples of powders, as well as to measure the mass fraction of the elements contained in the samples of contact elements from current collectors, we applied the energy-dispersive X-ray fluorescence analyzer "EXPERT 3L". Samples of the contact plates are chosen based on testing the compliance with the manufacturer's specifications, or for the content of actual components in a given sample. An example of the visualization of spectrum acquired at the energy-dispersive X-ray fluorescence analyzer "EXPERT 3L" for the contact plates BrIG is shown in Fig. 2.

In order to perform electrical measurements of resistance of contact pads in current collectors, we used the digital micrometer Megger DLRO 10X, which makes it possible under a fully automatic mode to choose the most suitable test current to 10 A d.c. to measure resistance from 0.1 µm to 2 000 Ohms, over one of the seven ranges. Results of the acquired measurements are used in the calculations and comparative estimation of the technological and operational stabilities, as well as indicators for parametrical reliability of pads made from different materials. These magnitudes make it possible to derive analytical expressions for the contact resistance of sliding contact connections of power circuits in electric rolling stock with respect to microhardness and specific resistances of materials used for contact elements at current collectors and the film on them.

4. 2. Procedure for studying of process of wear and current collection from the sliding contact elements in current collectors used by electric transport

Estimation of wear resistance of the contact elements was carried out in accordance with the devised procedure for a comparative quality assessment of contact plates (Fig. 3).

In contrast to known assessments of indicators for parametric reliability in the operation of strong-current sliding contacts, in the course of a comprehensive study into the contact elements at current collectors used by electric rolling stock based on the criteria of wear and contact resistance, we introduced to calculations a correlation relationship between contact resistance and temperature of the sliding contacts. Indicators for operational reliability are refined taking into consideration the influence of contact pressure on the contact wire, which accounts for the design features of inserts or pads at a current collector, as well as and operating conditions.

The peculiarity of wear in the contact wires is the formation of a contact plane with the maximally permissible values for each brand of the contact wire at different motion speeds along the section. In this case, a plane forms at the contacting surface of the wire itself, which under dry friction will intensively wear out pads in current collectors, as well as the contact wire itself. Under operation, they do not allow the wear in the contact wire at the predefined maximum value. For example, for the most common copper wire MF–100 with an area of intersection of S=100 mm², this magnitude is 35 mm², which corresponds to height h=7.77...7,64 mm [33]. Therefore, when designing an installation for testing the operational properties and studying the process of wear and current collection from sliding electrical contacts we used a copper bus 10×2.5 mm rather than the contact wire.

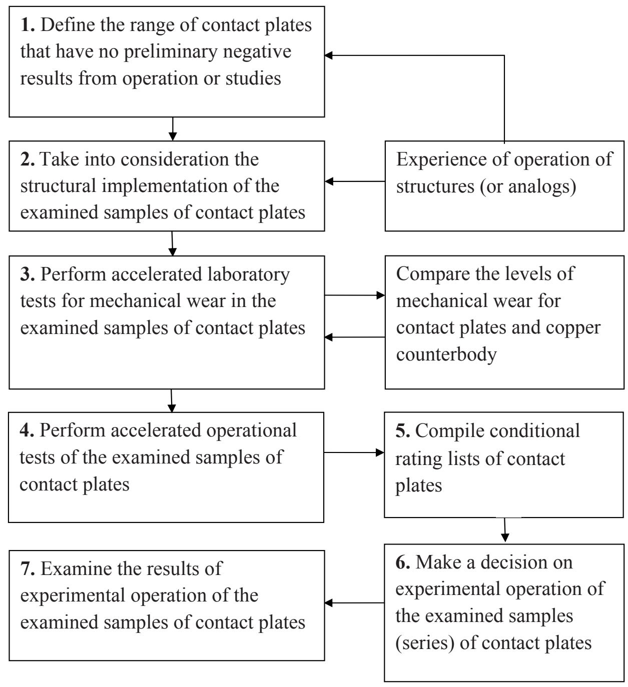


Fig. 3. Procedure for a comparative quality assessment of contact plates

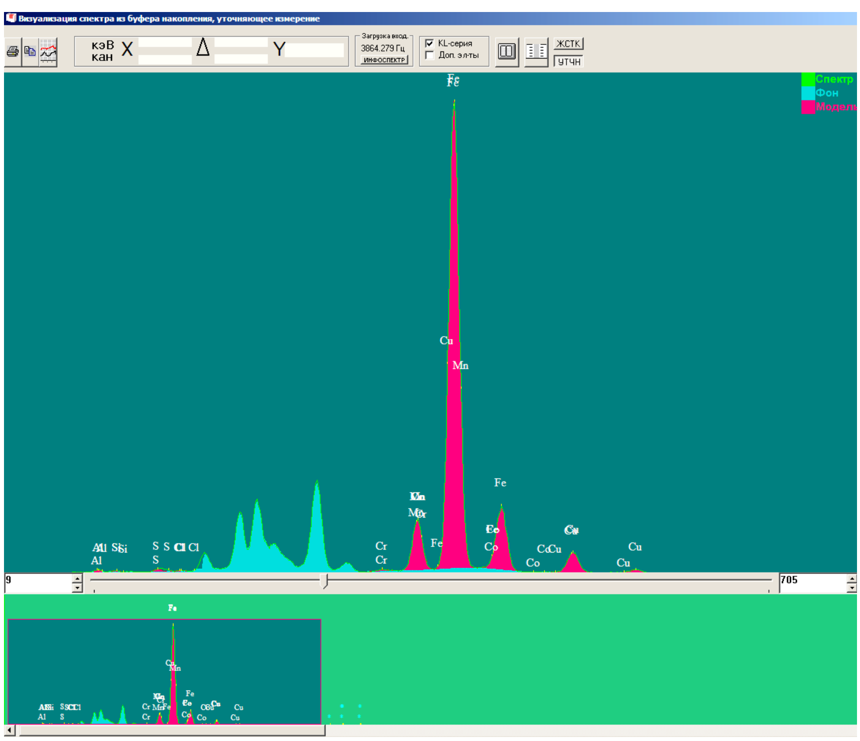


Fig. 2. Results from energy-dispersive analysis of the contact plate BrIG

During tests, we simulate the maximum wear of the contact wire for the maximum contact area in the sliding contact pair "electric transport current collector – contact network". This creates 4 times stricter conditions for testing the contact plates than it is regulated by GOST 32680-2014 [32]. Given that the contact network is not perfectly even in the plan, we simulate a slight lateral deflection of the contact bus ±0.5 mm at the points of contact with plates that are diametrically opposed and pressed with an adjustable effort of 40±8 N [32]. All the "contact network's irregularities" are tracked by the two spring-loaded "floating" carriages, which hold the examined contact elements in a current collector.

A special feature is the arrangement of contact elements in the carriage itself – the upper one is across the contact disk of installation, and the lower one is lengthwise, making it possible to test contact elements form any type of electric transport without additional resetting of the installation (Fig. 4).

a

b

Fig. 4. Passing over a "gap" in the contact wire by a contact plate under a current load in the spring-loaded "floating" carriages: *a* – upper cross contact; *b* – bottom longitudinal contact

In addition, the contact ring that simulates the contact wire is not solid, and has an intentional junction. When passing the junction, the contact plate undergoes a transient process that simulates a brief detachment of the current collector's skid from the contact wire. This is analogous to the passage of the contact brush in a motor over a collector plate. That provides for an additional possibility to conduct tests for any pair of the sliding contact.

Given that tests should involve different modes of operation, from low to the maximally permissible motion speeds at a regulated current strength, the installation is equipped with a switch to change the positions in steps. Controlled speed is adjustable in the range of 5...150 km/h; current is regulated within 0...500 A.

Prior and after testing, the contact plates are weighted; thickness of the plate in a contact zone with the contact wire is measured using a micrometer in line with GOST 6507-90; height of the contact bus is measured at ten control points. Over the entire time of testing we control temperature of the contact pair of the sliding contact "pad in a current collector at electric rolling stock – the contact wire" using the thermoelectric digital thermometer TT-C016-01.

5. Results of testing the contact plates

In order to confirm a possibility of using the contact material BrIG for pads in the current collectors at high-speed and industrial electric transport, we performed a study at various speeds and currents. Results from bench tests of the contact pads (inserts) BrIG in current collectors for electrical transport at different speeds and currents are summarized in Table 1.

Table 1

Results from bench tests of the contact pads (inserts) BrIG for current collectors used by electrical transport at different speeds and currents

No.	Type and material of pad (insert)	Position at the bench relative to the rotating disk	The number of pad's runs (disk rotations)	Mileage of pad (insert), km	Wear of pad (insert), mm Specific wear mm/km	State of the pad surface (insert)	Wear of copper bus, mm	State of the surface of copper bus
1	BrIG "+"	Atop, across	10,000 rotations *I*=100 A *V*=110 km/hour	14.287	0.10 0.007	Smooth, light, gloss, without scratches	0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05	Smooth, gloss, no scratches, no chips *T*max= =84 °C
2	BrIG "–"	At bottom, longitudinal		14.287	0.12 0.008	Smooth, light, gloss, without scratches		
1	BrIG "+"	Atop, across	10,000 rotations *I*=350 A *V*=75 km/hour	14.287	0.18 0.013	Smooth, light gloss, without scratches	0.06 0.05 0.06 0.05 0.05 0.05 0.05 0.05 0.06 0.06	Smooth, gloss, no scratches, no chips *T*max= =115 °C
2	BrIG "–"	At bottom, longitudinal		14.287	0.20 0.014	Smooth, light gloss, without scratches		
1	BrIG "+"	Atop, across	10,000 rotations *I*=500 A *V*=60 km/hour	14.287	0.25 0.017	Smooth, dark, gloss, without scratches	0.09 0.08 0.08 0.06 0.06 0.06 0.07 0.06 0.08 0.09	Smooth, gloss, no scratches, no chips *T*max=158 °C
2	BrIG "–"	At bottom, longitudinal		14.287	0.32 0.22	Smooth, dark, gloss, without scratches		

Note: "+" and "–" – polarity of current supply to the contact plates at the testing installation

After the test, we estimated the state of the contact surface of the contact plates BrIG and other contact pads and inserts, as well as the contact surface of a counter-body – a copper strip. The surface of the copper bus that simulates a contact wire demonstrates clear graphitized gloss after all operational modes of the contact plates BrIG (Fig. 5).

a *b*

Fig. 5. Results from bench tests of the contact plates BrIG: *a* — contact plates BrIG; *b* — gloss on a contact bus

Only at current strength of 500 A and speed of 10 km/h did we observe the heating of the contact plate above 160 °C and burn in the place of the contact bus when the contact plate under a current load passed over a "break" (Fig. 4). For all other modes of research, neither overheating of the contact plate nor burning in the place of break of the contact bus were registered (Table 1).

The state of the contact plates BrIG is satisfactory, the friction zone has no mechanical damage – no chips, scratches, breaks. The surface area under friction demonstrates a good graphitization; after cleaning the contact surfaces with gasoline, one can see that the contact zone is clear. No signs of damage, no changes in the structure, dimensions, were detected (Fig. 5).

After testing the contact plates (inserts) made by other manufacturers, the surface of the copper bus that simulates a contact wire does not exhibit any graphitization. In some cases, the opposite is true: there are chips in a contact pair. After testing coal contact inserts, we observed the transport of graphite particles without scratching and chips, but, when compared with other metallized samples, the insert is rapidly worn out (Table 2).

All the samples made from the new material BrIG have successfully passed the bench tests according to the procedure for testing, which has been verified by respective documents and protocols. The board concluded: "Samples of the contact plates BrIG" TU U 31.2-2237310075-001:2017 "The contact plate BrIG for current collectors used by electrical transport. Specifications" meet the requirements of DSTU GOST 32204:2016 (GOST 32204-2013, IDT) "Current collectors for train electric rolling stock. General specifications" and requirements by GOST 32680-2014 "Current-collecting elements of contact current collectors for electrical rolling stock. General technical specifications" and can be used by electrical rolling stock".

Table 2

Results from bench tests of contact pads (inserts) in current collectors used by electric vehicles, made by different manufacturers

No.	Type and material of pad (insert)	Position at the bench relative to the rotating disk	The number of pad's runs (disk rotations)	Mileage of pad (insert), km	Wear of pad (insert), mm Specific wear mm/km	State of the pad surface (insert)	Wear of copper bus, mm	State of the surface of copper bus
1	Coal insert, type B	Atop, across	117	0.167	2.5/14.97	Rough, shells, graphite discharge	0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01	Smooth, residue of graphite, no scratches no, chips
2	Coal insert, type B	At bottom, longitudinal		0.167	2.5/14.97	Rough, shells, graphite discharge		
3	BrIG	Atop, across	500,000	714.35	1.1/0.0015	Smooth, gloss, no scratches	0.2 0.2 0.2 0.1 0.1 0.2 0.1 0.1 0.1 0.2	Smooth, clear, gloss, no scratches, no chips
4	BrIG	At bottom, longitudinal		714.35	1.3/0.0018	Smooth, gloss, no scratches		
5	PKD-4-2	Atop, across	602	0.86	0.05/0.058	Rough, shells, copper chipping	0.3 0.3 0.1 0.2 0.2 0.2 0.3 0.2 0.2 0.3	Dark, scratched, chips, shells
6	PKD-4-2	At bottom, longitudinal		0.86	0.07/0.081	Rough, shells, copper chipping		

6. Discussion of results from comparative tests of contact elements in current collectors

The results, derived in the present work, could be considered valid enough, because they are based on both the comprehensive character of the technology, used to construct the pads, and the comprehensive character of the procedure for comparative assessment of products' quality.

The advantage of the proposed pads over those applied at present time on railroad is the perfect combination of innovative technologies, which fully meet partially contradictory operational requirements to them.

When carrying out such a study, one should take into consideration the subjective character of expert estimations, which, however, was minimized owing to the application of the innovative method of hierarchical comparison of pads' characteristics.

The disadvantages of this study include the lack of long-term operating tests of pads, aimed at the introduction of the new pads to industrial production, although it is a benefit. Our study could continue by standardizing the approaches considered here with their further introduction to acting regulatory framework.

In contrast to similar research, the initial data implied the "strictest" mode of contact between a pad and the contact wire for a pantograph pad – cutting a skid in one area of contact.

The process of plate wear at a bench is also different from the conditions of contact between an insert of a rod current collector in a trolley bus as it has a linear contact zone across, while trolley buses have at best two planes, and in the worst case, it is a longitudinal line.

At the stage of planning the further research, we deliberately impose "critical" modes of pad operation, which in some cases considerably exceed the requirements by DSTU 32680-2014. Therefore, it is impossible to predict the behavior of a contact plate made from any contact material. However, it becomes even more interesting at the next stage to investigate a contact surface following the interaction.

The results of comprehensive bench tests were summarized and implemented to pilot production and monitored operation at the locomotive, wagon, and trolley bus depots.

7. Conclusions

1. By employing a designed test installation, we carried out comparative tests of contact plates, which make it possible to assess the interaction with the contact wire in a minimally narrow zone that simulates "cutting" a pad. The results of research into wear magnitudes, tribotechnical and operational properties of pads in current collectors made from known contact materials, demonstrate that in the minimally critical contact zone of testing only the contact plates BrIG ensured maintaining the contact surface of a copper bus without scratching, chipping, and kept the contact plate itself. Both surfaces were smooth, with clear gloss.

2. Based on the main criteria for comprehensive bench and operational tests – wear resistance and durability, we estimated the technological and operational indicators of parametric reliability of pads for current collectors made from different materials for the criterion of their wear. The best results were demonstrated by pads for current collectors made from the contact material BrIG, based on bronze, iron, and graphite. The results obtained show that only the contact plates BrIG have passed the tests in the minimally critical contact zone. In terms of wear resistance of a material, the BrIG pads outperform PKD-4 by 37 times and the coal insert of type B by 9,356 times.

3. Confirmation of these laboratory and bench tests is successful application of the BrIG pads under conditions of actual operation. On railroad transport, the BrIG plates are used at the locomotive depot Lviv-West by the DC locomotives VL-10, VL11m for freight and passenger transportation, and by the AC locomotives of series VL 80 under a pusher mode. At the wagon depot Lviv, the BrIG plates replaced coal inserts at electrical trains of series ER-2 and EPL2t.

At trolley bus depot No. 1 in the city of Lviv the contact inserts BrIG have been used throughout the year of 2018 for all current collectors by trolley bus brands "Electron T19101", "Electron T19102", " koda 14Tr", jointed " koda 15Tr", LAZ-52522, ElektroLAZ-183. Operation is under way along various routes within the city at different loads under any weather conditions. Operation continues. At present, the experimental operation of the BrIG pads is to start at the skids of current collectors in tram carriages Tatra KT4, which will be tested under winter conditions along difficult tram sections in the city.

4. We have practically proved a possibility to prolong the service life of the contact pair "a pad in the current collector used by electric transport – the contact wire" by applying the new contact material BrIG. In terms of the main criteria, selected for the procedure of operational tests, specifically wear resistance and durability, the material BrIG showed better performance than the standard pads PKD-4 and the coal inserts of type B. At locomotives in passenger transportation, an increase in the resource of contact plates of the BrIG type, compared with the PKD plate, exceeds by 1.66 times; under a carrying mode at freight locomotives, exceeds by 1.90 times. At alternating current under an electric locomotive-pusher mode, an increase in the resource of contact plates of the BrIG type, compared with resource of the coal inserts of type "B", exceeds by 26.94 times. When applying inserts made from the BrIG material at trolley busses, compared with regular coal inserts, the selected indicators were outperformed by more than 68 times, depending on the operating conditions.

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