CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

Check for updates

UDC 621.86
https://doi.org/10.23947/2541-9129-2023-7-4-119-130

Original article

Wear Reduction in Heavily Loaded Units of Transport Vehicles

Aleksey A. Demyanov ✉, **Igor N. Shcherbakov**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ alexys61@yandex.ru

Abstract
Introduction. The pivot assembly provides connection between the rotating and non-rotating parts of machines and mechanisms such as cranes, excavators, trailers, railway rolling stocks. In relation to rolling stock, it connects the load-carrying part of the car with the bogie and is one of the most critical and wear-out friction units. Its technical condition affects the intensity and form of wear of the surfaces themselves, the amount of resistance to rotation of the bogie when the car moves in curved sections of the track, the amplitude of the lateral rocking of the car, the intensity of wear of the wheel flanges and, as a consequence, the safety of operation of the rolling stock as a whole. Until now, periodic grease is used for this unit, which, even with a short mileage, manages to be squeezed out of the contact zones and, thereby, creates conditions for the predominance of dry friction. Until now, various proposals to solve this problem have not found application in mass production for a number of reasons, and therefore the search for ways to reduce wear in the pivot assembly of cars is still relevant. This study proposes a solution to this problem that does not require structural changes to the pivot assembly itself. The aim of this work was to develop a technologically advanced anti-friction coating with good adhesion, which will be applied to the surface of a replaceable disk installed between the rubbing surfaces of the pivot assembly during scheduled repairs of the car chassis. This approach will reduce the friction force and wear rate in the unit when lubrication shortage occurs due to squeezing out of the grease.
Materials and Methods. Antifriction characteristics of the developed coating was observed on a friction machine providing specific loads on the test sample up to 5000 N and a sliding speed from 0.13 m/s. The samples were examined by scanning electron microscopy (FEI Quanta 200 microscope). SEM images were acquired in a back-scattered electron (BSE) mode using a semiconductor detector. To analyze the elemental composition of beam samples, an energy dispersive spectrometer (EDAX Element EDS system) was used.
Results. A three-layer functional phosphorus-containing composite coating of the surfaces of the unit was developed, which made it possible to significantly reduce the coefficient of friction and, as a consequence, the intensity of wear of the pivot unit surface during dry friction. The optimal conditions for obtaining composite coating layers were determined. The influence of the thickness of each layer and the conditions for its production on its functional characteristics was studied.
Discussion and Conclusion. The proposed solution is manufacturable and, with appropriate adaptation, can be used to reduce wear in any open pivot assembly without radically changing its design. The methods for producing coating layers are accessible and technologically advanced for serial use.

Keywords: rail rolling stock, pivot assembly, open friction assembly, composite multilayer coating, wear reduction

Acknowledgements. The authors would like to thank the editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For citation. Demyanov AA, Shcherbakov IN. Wear Reduction in Heavily Loaded Units of Transport Vehicles. *Safety of Technogenic and Natural Systems.* 2023;7(4):119–130. https://doi.org/10.23947/2541-9129-2023-7-4-119-130

Научная статья

Снижение износа высоконагруженных узлов транспортных средств

А.А. Демьянов ✉, **И.Н. Щербаков**
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ alexys61@yandex.ru

Аннотация

Введение. Опорно-поворотный узел обеспечивает связь между поворотной и неповоротной частью машин и механизмов кранов, экскаваторов, автоприцепов, железнодорожных подвижных составов. Применительно к подвижному составу он соединяет грузонесущую часть вагона с тележкой и является одним из наиболее ответственных и быстроизнашивающихся узлов трения. Его техническое состояние влияет на интенсивность и форму износа самих поверхностей, величину сопротивления повороту тележки при движении вагона на криволинейных участках пути, амплитуду боковой раскачки вагона, интенсивность износа гребней колес и, как следствие, на безопасность эксплуатации подвижного состава в целом. До сих пор для данного узла применяется периодическая консистентная смазка, которая даже при небольшом пробеге успевает выдавиться из зон контакта и тем самым создать условия для преобладания сухого трения. До настоящего времени различные предложения по решению этой проблемы не нашли применения в серийном производстве по ряду причин, и поэтому поиск путей снижения износа в опорно-поворотном узле вагонов до сих пор является актуальным. В данном исследовании предлагается решение этой проблемы, не требующее конструктивных изменений самого опорно-поворотного узла. Целью данной работы является разработка технологичного антифрикционного покрытия с хорошей адгезией, которое будет нанесено на поверхность сменного диска, устанавливаемого между трущимися поверхностями шкворневого узла во время плановых ремонтов ходовой части вагона. Такой подход позволит снизить силу трения и интенсивность износа в узле при наступлении смазочного голодания из-за выдавливания консистентной смазки.

Материалы и методы. Антифрикционные характеристики разработанного покрытия определялась на машине трения, обеспечивающей нагрузки на исследуемый образец до 5 000 Н и скорости скольжения от 0,13 м/с. Образцы исследовались методом сканирующей электронной микроскопии (микроскоп FEI Quanta 200). СЭМ-изображения получены в режиме регистрации обратно-рассеянных электронов (BSE) с помощью полупроводникового детектора. Для анализа элементного состава образца использовался рентгеновский энерго-дисперсионный спектрометр (EDAX Element EDS System).

Результаты исследования. Разработано трехслойное функциональное фосфорсодержащее композиционное покрытие поверхностей узла, позволяющее существенно снизить в нем коэффициент трения и, как следствие, интенсивность износа шкворневого узла из-за сухого трения. Определены оптимальные условия получения слоев композиционного покрытия. Изучено влияние толщины каждого слоя и условий его нанесения на функциональные характеристики.

Обсуждение и заключение. Предложенное решение отличается технологичностью и при соответствующей адаптации может быть использовано для снижения интенсивности износа в любом открытом опорно-поворотном узле без кардинального изменения его конструкции. Методы получения слоев покрытия доступны и технологичны для серийного применения.

Ключевые слова: рельсовый подвижной состав, шкворневой узел, открытый узел трения, композиционное многослойное покрытие, снижение износа

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, которые позволили повысить ее качество.

Для цитирования. Демьянов А.А., Щербаков И.Н. Снижение износа высоконагруженных узлов транспортных средств. *Безопасность техногенных и природных систем.* 2023;23(4):119–130. https://doi.org/10.23947/2541-9129-2023-7-4-119-130

Introduction. In railway transport, one of the most responsible and high-wearing friction units is the pivot assembly connecting the body to the bogie. A well-known problem of this unit is the squeezing out of lubricant from it, even with minor runs, followed by contact of surfaces in dry friction mode and the corresponding wear intensity [1].

Currently, planned restoration of worn-out pivot assemblies annually results in huge sums, even without taking into account losses from idle cars and the costs of their unscheduled repairs. If we take into account the fact that there are more than 1.3 million cars in circulation in our country, then the task of reducing friction and wear in this unit is urgent. This problem is sectoral on the scale of all industrially developed countries of the world [2]. To date, there are various approaches to solving this problem, which can be broadly divided into several principal groups.

The first group includes methods based on changing the design of the unit in order to increase the diameter of the support surface and, as a result, reduce specific loads. The disadvantage of this approach is the exclusion of interchangeability of unit elements during mass repairs. The second group includes methods in which replaceable inserts made of various polymer wear-resistant materials are installed between the rubbing surfaces in the form of a round pocket with annular grooves at the bottom for the accumulation of grease. The presence of a replaceable element reduces the cost of repairing this unit. However, in severe operating conditions of the pivot assembly, polymer materials have a very short service life. The third group includes methods in which replaceable inserts made of high-strength steels, for example, manganese steel, are installed between the rubbing surfaces. However, this approach does not exclude the wear of the surface of the pivot assembly itself. After the inevitable squeezing out of viscous lubricant, wear intensity will be determined by the ratio of hardness of the contacting surfaces of the removable disk and the main unit. The fourth group of methods includes methods for improving heat treatment of contacting surfaces.

Another solution to eliminate increased friction in the pivot unit is to install a less rigid disk with holes distributed over its entire surface between the rubbing surfaces. The perforation in the disc is filled with solid grease. The supply of lubricant to the friction surface in this case is adaptive and is determined by the intensity of wear on the surface of the replaceable disk (Fig. 1) [3].

Since squeezing out of viscous lubricant and periodic contact of surfaces in the dry friction mode in this unit is inevitable, it is proposed to increase the durability of this unit by reducing the intensity of wear by installing a replaceable disk with a durable and technologically advanced antifriction coating between the friction surfaces. With this approach, lack of lubrication during squeezing out of regular grease will have less effect on the intensity of wear and, as a result, prolong the durability of this unit [4–6].

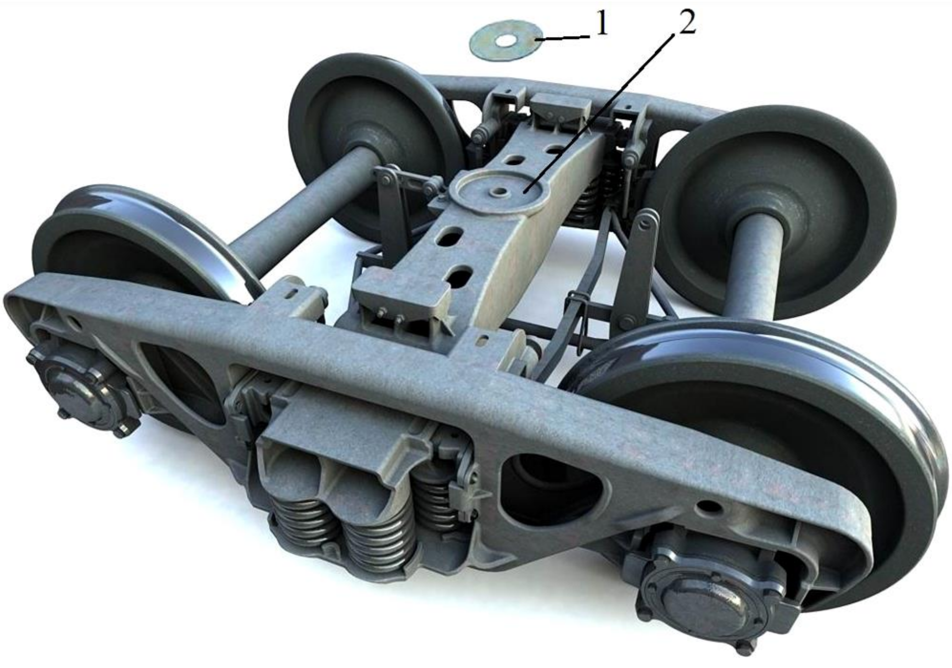


Fig. 1. Pivot assembly of the rolling stock: 1 — replaceable disk; 2 — frame with a center plate

Modification of surfaces with functional coatings is a well-proven method of increasing the wear resistance of components operating under difficult conditions — under high loads, absence or interruptions in the supply of lubricant to the friction zone, in aggressive abrasive media, etc. [7–13].

In this study, the aim was to develop a coating that provides a low coefficient of friction on surfaces, as well as creating conditions for rigid dynamic contact of reliable adhesion with the material of the coated product.

Materials and Methods. It was decided to solve this problem by developing a three-layer coating from a combination of several layers of a phosphorus-containing composite [14]. In order to comply with the specified requirements, the influence of the thickness of each layer and the conditions of its manufacture on its functional characteristics was studied. The coating was applied in layers. Chromium steel was chosen as the material for the base, i.e. the replaceable disc.

The first layer to be applied consisted of a composite nickel-phosphorus compound modified with molybdenum disulfide. Its task was to ensure high adhesion to the substrate. This layer was obtained by chemical deposition. The subsequent layer was made on the basis of a phosphate binder [14, 15], the task of which was to ensure the binding of the first layer with the third and increase corrosion resistance due to the fact that the bogie pivot was an open friction unit. In order to reduce the cost and increase the manufacturability, the layer was obtained by several simple and technological methods (spraying, dipping and spreading), followed by a comparative assessment of its functional properties. The third layer, which provided antifriction properties, was also obtained by spraying and spreading, followed by a comparative assessment of its properties [14, 15].

The adhesion quality of the layer to the previous one was assessed by the results of the cross-cut test by an adhesion tester[1]. The thickness of each layer was measured by a combined-action thickness gauge. The antifriction parameters of the third layer were determined using an AI 5018 friction machine. The analysis of the surface of the layers was carried out by scanning electron microscopy on a FEI Quanta 200 microscope. SEM images were obtained in the backscattered electron (BSE) registration mode using a semiconductor detector. An X-ray energy dispersion spectrometer EDAX Element EDS System was used to analyze the elemental composition of the sample.

Statistical processing of the results of the experimental studies was carried out by computer methods of processing the results of an engineering experiment.

In the course of the research, the conditions influencing the final parameters of the resulting coating were determined. The following influence was investigated:

– of the temperature of the solution on the thickness of the resulting coating;

– of the thickness of the third layer on its adhesion to the previous one;

– of the thickness of the third layer and the conditions for its production on the value of its friction coefficient.

The first layer (nickel-phosphorus coating) was obtained by chemical deposition. To ensure the sedimentation stability of the modifiers present in the chemical precipitation solution, a PE-6110 magnetic mixer with a heating function was used. The deposition process of this layer took place under conditions of 90-92°C. The adhesion of the coating to the substrate was evaluated according to the standard procedure for such cases[2]. The second layer (phosphate coating), according to the idea, was applied by three different methods: dipping, spreading and spraying [14]. The third (antifriction) layer was obtained by several methods — spraying and spreading over a phosphate binder [15].

Since the layers of the resulting composite coating are not operable without heat treatment, the effect of the heat treatment modes of the layers on their final properties was investigated, followed by the selection of the optimal mode for each of them.

After application to the first, the second layer was subjected to heat treatment at a temperature of 250 to 400°C for one hour. The heat treatment mode did not depend on the method of applying the second layer. It was selected experimentally taking into account the best indicators for the number of through pores to the base [11]. After applying the third layer to the second one, its heat treatment was carried out in the temperature range from 300 to 450°C for one hour. To study antifriction properties of the third layer, depending on the temperature of heat treatment, a model test of several samples obtained at different temperatures was carried out.

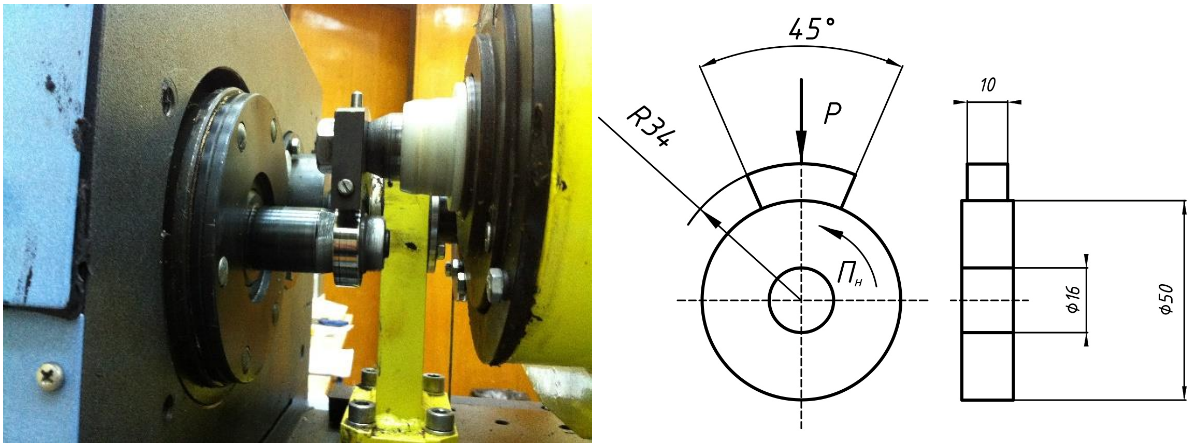
The determination of friction characteristics of the third layer was carried out according to the "disk-pad" scheme. The coating was applied to the "pad" sample. The general view and coupling scheme of the samples are shown in Figure 2.

[1] *Paints and varnishes. Cross-cut test*. ISO 2409:2020. https://www.iso.org/standard/76041.html

[2] GOST 9.302-88. *Unified system of corrosion and ageing protection. Metal and non-metal inorganic coatings. Control methods.* URL: https://gostrf.com/normadata/1/4294850/4294850372.pdf (In Russ.).

When assigning the load for the model experiment, it was assumed that the most common type of rolling stock were high sided wagons of various modifications with an average load capacity of about 70 tons and a mass of 23 tons. Taking into account the fact that each support unit accounted for half of the total weight, and the diameter of the center pivot and the diameter of the pin hole were 302 and 54 mm, respectively, the actual contact pressures were obtained, which amounted to 6.7 MPa.

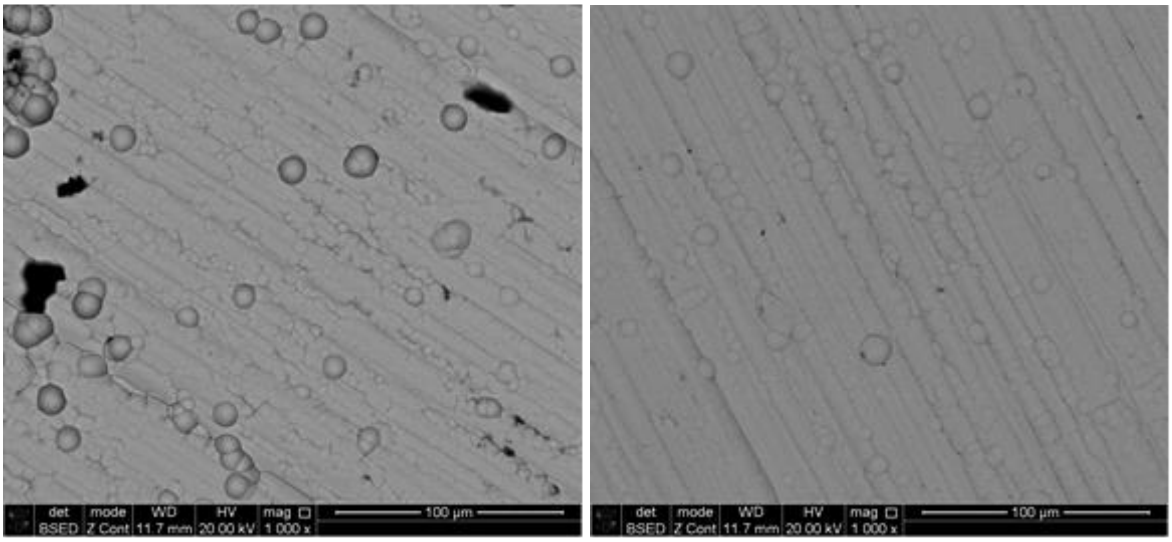
The speed of relative sliding of surfaces in the pivot assembly is determined by the radius of the curve and its current speed, set by the driver depending on the traffic conditions. Since in practice the sliding speed had small values, the minimum possible rotational speed of the shaft of the lower sample, 50 min^{-1}, was adopted for a comparative study between the samples.



a) *b*)

Fig. 2. Samples of "disk-pad": *a* — general view; *b* — coupling scheme

Results. During the study, it was found that the first layer was best obtained by using chemical deposition at a rate of up to 40 microns/h. A significant influence on the thickness and quality of the resulting coating was by the temperature of the solution and the concentration of the components. Based on the obtained adhesion measurement results, it was found that the heat treatment of the first layer was best at a temperature of 400°C for one hour. At this temperature, the Ni phase and wear-resistant Ni_3P were formed [14, 15]. Micrographs of the layer are shown in Figure 3, the element analysis in Tables 1 and 2, and the distribution of elements in the first layer is shown in Figure 4.



a) *b*)

Fig. 3. Micrographs of the first layer:

a — before heat treatment; *b* — after treatment for one hour at a temperature of 400°C

Table 1

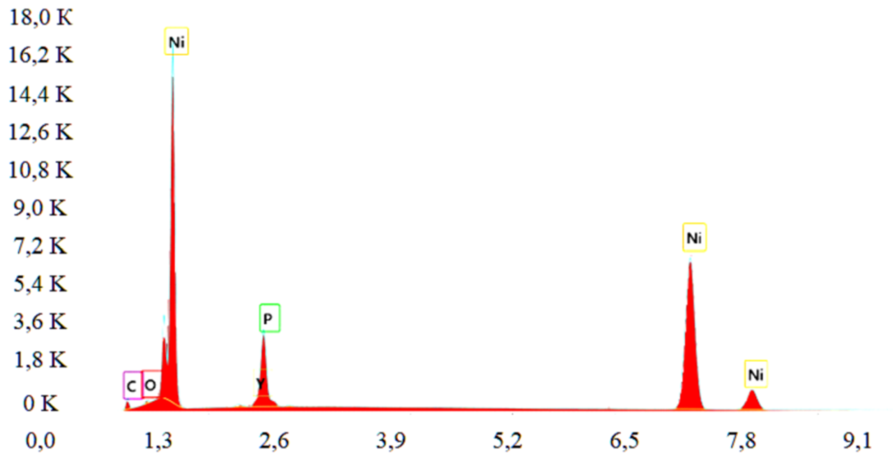
Elemental analysis of the first layer before heat treatment

Element	Weight %	MDL	Atomic %	Error %
C K	8.3	0.56	28.5	14.1
O K	0.6	0.22	1.6	23.5
P K	9.3	0.12	12.5	7.0
Ni K	79.9	0.41	56.4	2.2
Y K	2.1	0.22	1.0	10.7

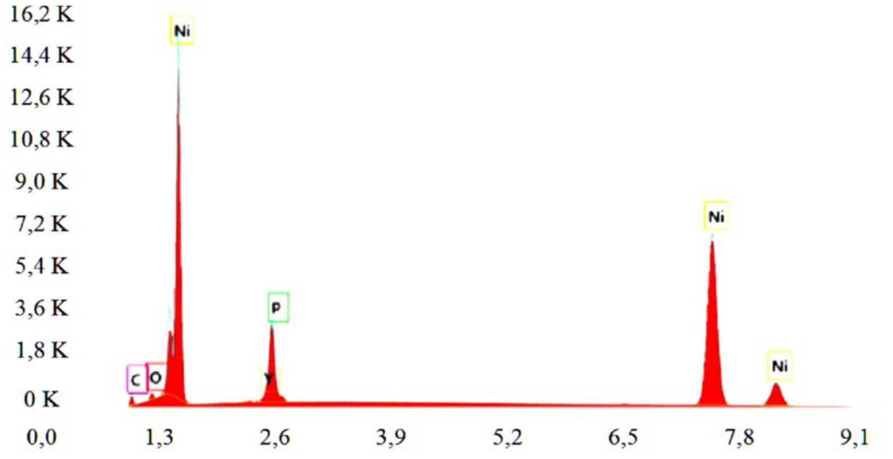
Table 2

Elemental analysis of the first layer after heat treatment

Element	Weight %	MDL	Atomic %	Error %
C K	7.6	0.52	26.5	14.2
O K	1.4	0.19	3.6	13.5
P K	8.9	0.14	12.0	7.0
Ni K	80.1	0.33	57.0	2.2
Y K	2.1	0.20	1.0	10.7



a)



b)

Fig. 4. Distribution of elements in the first layer:

a — before heat treatment; *b* — after treatment for one hour at a temperature of 400°C

Figure 5 shows a micrograph of the second layer, and Figure 6 shows the dependence of the change in the thickness of the second layer on the temperature of heat treatment and the method of coating. According to the test results, it was found that at a heat treatment temperature of 350°C for one hour, the lowest coefficient of friction for this coating was 0.07. This was significantly less in comparison with the initial coefficient of friction of 0.10–0.12 during normal operation of the unit and up to 0.18 when the lubricant was squeezed out. Table 3 provides the data on the study of antifriction properties of the third layer, depending on the temperature of its heat treatment. The proposed coating provided a reduction in the coefficient of friction by almost half, compared with the original node, even with dry friction.

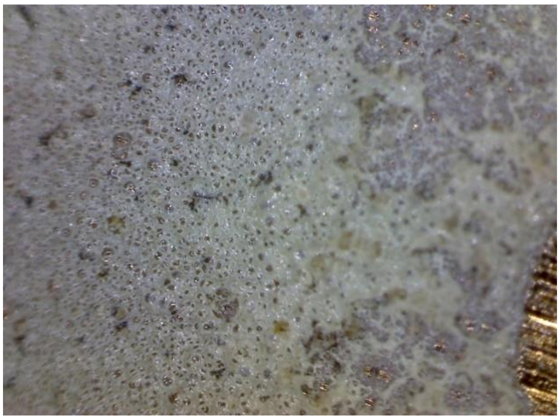


Fig. 5. Micrographs of the second layer, ×200

Table 3

Influence of the temperature of heat treatment of samples on their antifriction properties

Heat treatment temperature , °C	300	350	400	450
Coefficient of friction	0.09	0.07	0.09	0.12

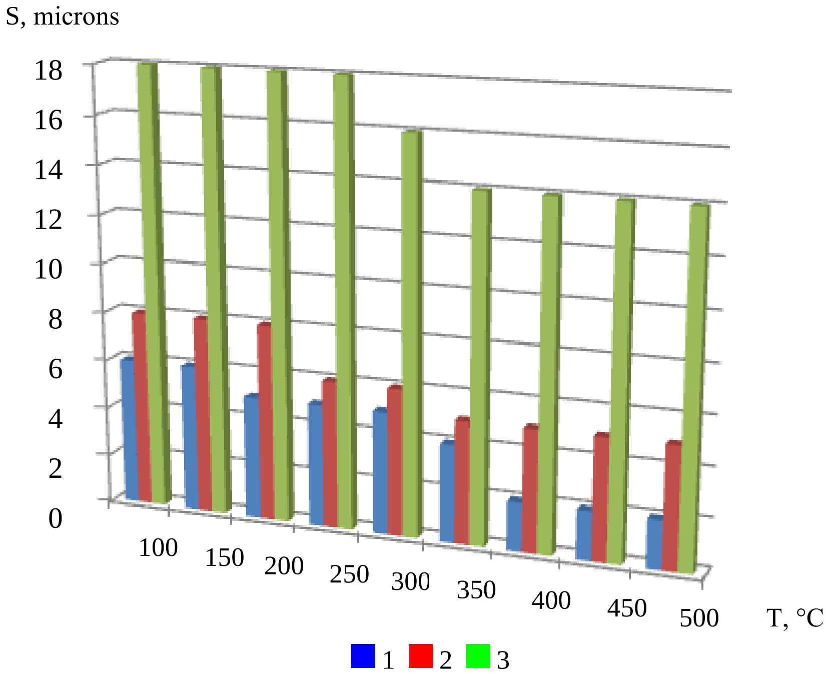
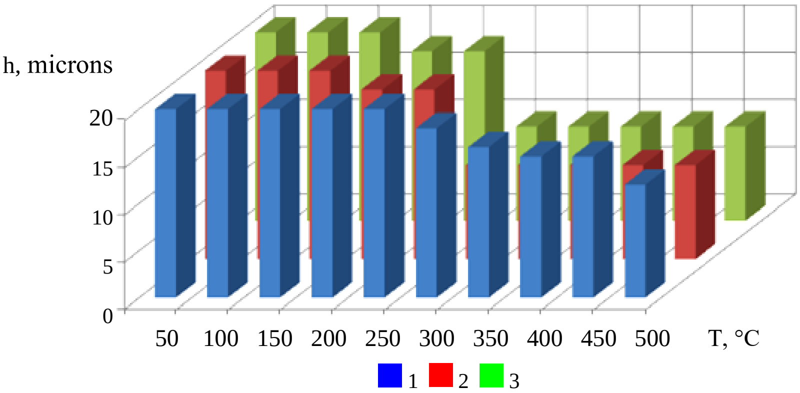


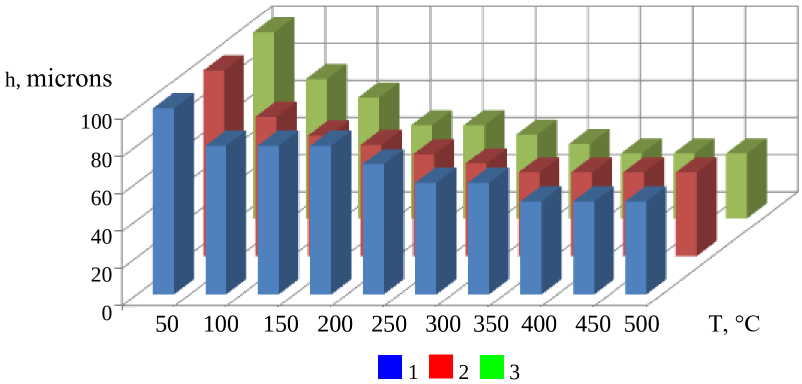
Fig. 6. Change in thickness of the second layer obtained depending on the temperature of heat treatment and the method of coating: 1 — spraying method; 2 — dipping method; 3 — spreading method

The dependence of the third layer thickness on the temperature and duration of heat treatment is shown in Figure 7.

Figure 8 shows a micrograph, and Figure 9 shows an elemental analysis of the third layer obtained at a heat treatment temperature of 350°C for one hour.



a)



b)

Fig. 7. Change in the third layer thickness at different combinations of temperature and heat treatment time:
1 — 60 min.; 2 — 120 min.; 3 — 180 min.;
a — coating is obtained by spraying; *b* — coating is obtained by spreading

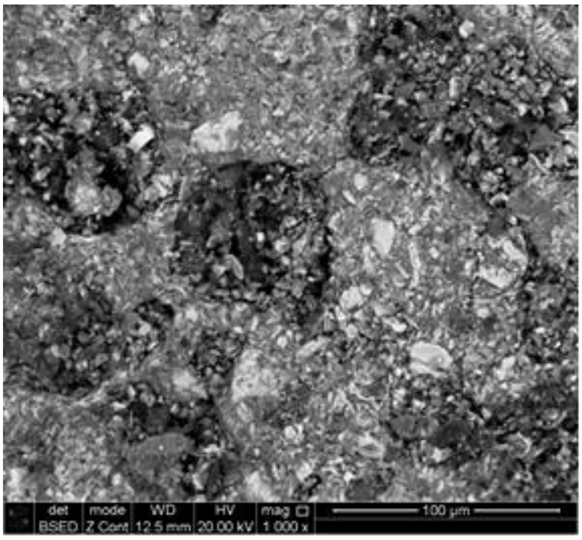


Fig. 8. Micrographs of the third layer

When measuring the adhesion of the third layer, depending on its thickness (Fig. 10), it was found that the best values of the results were obtained with a coating thickness of no more than 20 microns, which was considered optimal.

Based on the results of the obtained dependencies, a recommendation was formed to achieve optimal parameters of the last antifriction layer of the composite coating (Table 4)

Table 4

Values of optimal parameters for the antifriction layer

Element	Weight %	MDL	Atomic %	Error %
O K	35.7	0.23	60.3	10.6
Ne K	0.3	0.13	0.5	24.1
Mg K	1.3	0.10	1.5	10.2
P K	17.4	0.09	15.2	4.7
S K	14.3	0.37	12.1	5.0
Fe K	1.7	0.19	0.8	8.5
Ni K	2.5	0.28	1.1	7.8
Zn K	7.1	0.33	2.9	4.9
Sr L	0.6	0.15	0.2	11.2
Mo L	17.6	0.85	5.0	5.4
Cd L	1.5	0.23	0.4	17.8

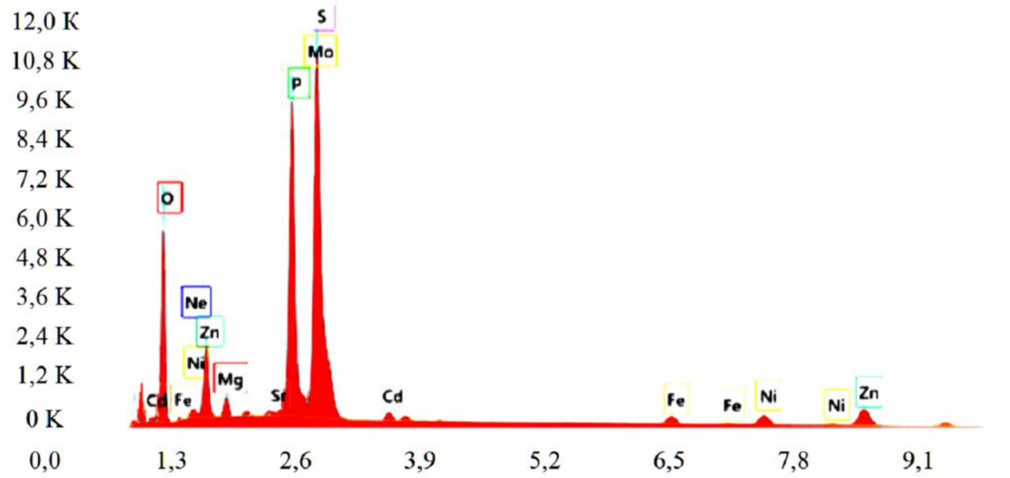


Fig. 9. Elemental analysis of the third layer

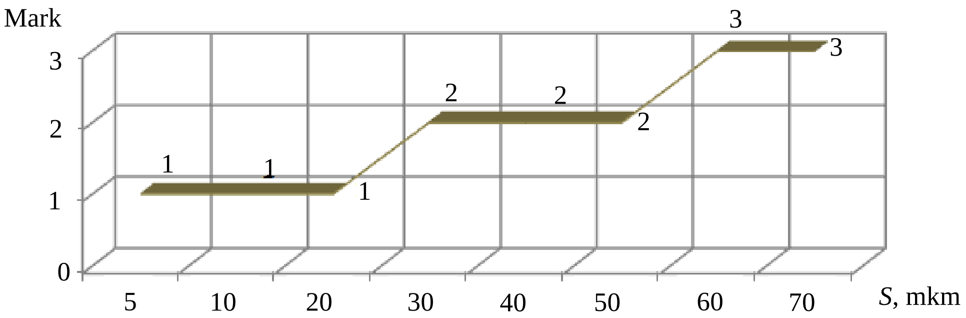


Fig. 10. Change of adhesion of the third coating layer depending on its thickness

Discussion and Conclusion. According to the results, the sample obtained at a heat treatment temperature of 350°C and exposure for one hour provides the lowest possible coefficient of friction for this coating. According to the authors, this is due to the fact that an increase in temperature above 350°C causes the appearance of oxide structures that increase the coefficient of friction. The temperature below 350°C does not allow the formation of phosphorus-containing phases that increase the antifriction properties of the third layer, which corresponds to previous studies [15].

The results obtained will increase the durability of the unit itself, reduce the wear of the ridges of wheels and rails and improve transportation safety.

The obvious advantages of the proposed solution include the facts that it:

– does not require fundamental changes in the design of the friction unit;

– is characterized by the simplicity and manufacturability of coating;

– does not require significant material costs;

– does not cancel the use of routine lubrication, but complements it;

– is universal.

The proposed solution may well be applied in any units, for example, in coupling devices of automobile rolling stock, various assemblies of lifting and transport machines, units of technological equipment, etc.

References

1. Bykov BV. *Konstruktsiya i tekhnicheskoe obsluzhivanie gruzovykh vagonov.* Moscow: Zheldorizdat Transinfo; 2006. 125 p. (In Russ.)

2. Pavlitskii BI. *Povyshenie nadezhnosti oporno-povorotnykh ustroistv na osnove printsipa postroeniya adaptivnykh sistem.* Author's thesis. Rostov-on-Don; 2018. 138 p. (In Russ.)

3. Demyanov AA, et al. *Shkvornevaya Sistema.* Patent RF, No. 2513093. 2014. 5 p. URL: https://www.freepatent.ru/patents/2513093 (accessed 02.10.2023). (In Russ.)

4. Demyanov A, Demyanov A, Pavlitskiy B, Sherbakov I, Shapshal A, Shapsha S. Reliability improvement of heavy machineries friction units. In: *IOP Conference Series: Earth and Environmental Science.* 2019;403:012015. https://doi.org/10.1088/1755-1315/403/1/012015

5. Fedyaeva EA, Olshevskii AA. Modelirovanie iznosa pyatnikovogo uzla gruzovogo vagona. *Bulletin of Bryansk state technical university.* 2009;(3(23)):83–86. (In Russ.)

6. Motovilov KV (ed.), Lukashuk VS, Krivorudchenko VF, Petrov AA. *Tekhnologiya proizvodstva i remonta vagonov*. Moscow: Marshrut; 2003. 382 p. (In Russ.)

7. Shashkeev KA, Popkov OV, Yurkov GY, Kondrashov SV, Ashmarin AA, Biryukova MI. Composite tribological materials based on molybdenum disulfide nanoparticles and polytetrafluoroethylene microgranules. *Russian Journal of Applied Chemistry.* 2016;89(4):644–649. https://doi.org/10.1134/S1070427216040194

8. Xiaoming Chen, Liuyang Zhang, Cheol Park, Catharine C. Fay, Xianqiao Wang, Changhong Ke. Mechanical strength of boron nitride nanotube-polymer interfaces. *Applied Physics Letters.* 2015;107(25):253105. https://doi.org/10.1063/1.4936755

9. Kucernak ARJ, Venkata N Naranammalpuram Sundaram. Nickel phosphide: the effect of phosphorus content on hydrogen evolution activity and corrosion resistance in acidic medium. *Journal of Materials Chemistry A*. 2014;2:17435–17445. https://doi.org/10.1039/c4ta03468f

10. Kumaravelu P, Arulvel S, Kandasamy J. *Coatings and surface modification techniques for additive manufacturing in innovations in additive manufacturing surface.* In: Khan M.A., Jappes J.T.W. (eds) Innovations in Additive Manufacturing. Springer Tracts in Additive Manufacturing. Springer, Cham. 2022. P. 221–238. http://doi.org/10.1007/978-3-030-89401-6_10

11. Ren Ping, Zhang Shangzhou, Qiu Jianxun, Yang Xiaoyang, Wang Weiwei, Li Yang et al. Self-lubricating behavior of VN coating catalyzed by solute Ag atom under dry friction and oil lubrication. S*urface and Coatings technology.* 2020;409:126845. http://doi.org/10.1016/j.surfcoat.2021.126845

12. Ji Lianggang, Chen Zhaoqiang, Guo Runxin, Xu Chonghai, Guo Niansheng. Preparation of nano-coating powder CaF2Al(OH)3 and its application in Al2O3/Ti(C,N) self-lubricating ceramic tool materials. *Ceramics International*. 2020;46(10.B):15949–15957. http://doi.org/10.1016/j.ceramint.2020.03.144

13. Pinate S, Leisner P, Zanella C. Wear resistance and self-lubrication of electrodeposited Ni-SiC:MoS2 mixed particles composite coatings. *Surface and Coatings technology.* 2021;421:127400. https://doi.org/10.1016/J.SURFCOAT.2021.127400

14. Shcherbakov IN, Trofimov GYe, Derlugyan PD, Loginov VT, Gerken NV. *Sposob polucheniya kompozitsionnogo antifriktsionnogo pokrytiya*. Patent RF, No 2556155. 2015. URL: https://patents.s3.yandex.net/RU2556155C2_20150710.pdf (accessed: 02.10.2023) (In Russ.)

15. Shcherbakov IN. Receiving features and properties of the composition multilayered solid lubricant coatings. *Bulletin of Higher Educational Institutions. North Caucasus region. Technical Sciences.* 2016;(2):97–101. https://doi.org/10.17213/0321-2653-2016-2-97-101 (In Russ.)

16. Scherbakov IN, Ivanov VV, Derlugian PD, Loginov VT. Preparation and properties of a composite solid lubricating coating. *Bulletin of Higher Educational Institutions. North Caucasus region. Technical Sciences.* 2015;(4):89–92. https://doi.org/10.17213/0321-2653-2015-4-89-92 (In Russ.)

Received 05.10.2023
Revised 18.10.2023
Accepted 01.11.2023

About the Authors:

Aleksey A. Demyanov, Cand. Sci. (Eng.), Associate Professor, Associate Professor of the Transport Systems and Logistics Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), SPIN-code: 8504-0447, ORCID, ScopusID, alexys61@yandex.ru

Igor N. Shcherbakov, Cand. Sci. (Eng.), Associate Professor, Associate Professor of the Transport Systems and Logistics Department, Don State Technical University, (1, Gagarin Sq., Rostov-on-Don, 344003, RF), SPIN-code: 6729-6905, ORCID, ScopusID, ResearcherID, bdd-don@mail.ru

Claimed contributorship:

AA Demyanov: formulation of the basic concept, processing of the research results, provision of resources, preparation of the text of the article;

IN Shcherbakov: preparation of the experiment, testing of samples, processing of the research results, preparation of the text of the article.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 05.10.2023
Поступила после рецензирования 18.10.2023
Принята к публикации 01.11.2023

Об авторах:

Алексей Александрович Демьянов, кандидат технических наук, доцент, доцент кафедры эксплуатации транспортных систем и логистики Донской государственный технический университет (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 8504-0447, ORCID, ScopusID, alexys61@yandex.ru

Игорь Николаевич Щербаков, кандидат технических наук, доцент, доцент кафедры эксплуатации транспортных систем и логистики Донского государственного технического университета, (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 6729-6905, ORCID, ScopusID, ResearcherID, bdd-don@mail.ru

Заявленный вклад соавторов:

А.А. Демьянов — формирование основной концепции, обработка результатов исследований, обеспечение ресурсами, подготовка текста статьи.

И.Н. Щербаков — подготовка эксперимента, испытаний образцов, обработка результатов исследований, подготовка текста статьи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.