

## Repair of damaged 76KhF steel rails using laser powder cladding

**A. B. Lyukhter**, *Cand. Eng., Associate Prof., Director of the Scientific and Educational Center for the Introduction of Laser Technologies*<sup>1</sup>, e-mail: 3699137@mail.ru;

**A. V. Zavitkov**, *Assistant Prof. of the Dept. of Heat Engines and Electrical Installations, Head of the Design and Technology Dept. of the Engineering Center*<sup>1,2</sup>, e-mail: vip.zavitkov@mail.ru;

**A. G. Akopian**, *Deputy Head of the Technical Policy Dept.*<sup>3</sup>, e-mail: akopian-rzd@yandex.ru;

**A. I. Nikolin**, *Cand. Eng., Director of the Scientific Certification Center “Welding” of the Scientific Center “Infrastructure”*<sup>4</sup>, e-mail: nikolin.arkady@vniizht.ru;

**N. A. Markov**, *Assistant of the Dept. of Heat and Gas Supply, Ventilation and Hydraulics, Engineer of the Experimental Production of the Scientific and Educational Center for the Introduction of Laser Technologies*<sup>1,2</sup>, e-mail: mnikita.markovm@gmail.com

<sup>1</sup> Vladimir State University named after Alexander and Nikolay Stoletovs (VlSU), Vladimir, Russia

<sup>2</sup> Vladimir Engineering Center for the Application of Laser Technologies in Mechanical Engineering at VISU, Vladimir, Russia

<sup>3</sup> Russian Railways (OJSC RZhD), Department of Technical Policy, Moscow, Russia

<sup>4</sup> Railway Research Institute of JSC Russian Railways (VNIIZhT), Moscow, Russia

The paper considers a method for repairing a rail track with wear defects acquired during long-term operation of a railway transport. Existing defects significantly reduce the carrying capacity of the railway section and affect the reliability and safety of the operation of elements of the upper structure of the railway track. The use of existing traditional repair methods has technological limitations. Experimental technology for repairing the rail defects is carried out under stationary conditions. The purpose of the work is to create a coating that meets the requirements of the regulatory documentation of Russian Railways (OJSC RZhD), and ensures the possibility of such work in the field conditions in limited time intervals between train movements (~40 min). The article presents the results of metallographic analysis and cyclic tests of the experimental samples of railway rails made of 76KhF steel category DT350 with a cladded coating by laser powder cladding. The quality assessment is carried out according to the following criteria: the absence of the defects such as pores, shrinkage cavities and cracks; the compliance of the metal hardness values with the operational requirements. The resulting cladded layer eliminates the risk of formation of the structures that can lead to a brittle destruction of the material, while meeting the established operational technical requirements, such as required strength, hardness and wear resistance, minimal thermal deformation and mechanical properties for the railway rails. Based on the study results, the proposed repair method enhances the feasibility of implementing this technology within Russian Railways (OJSC RZhD) infrastructure. It facilitates the elimination of defects up to 350 mm in length and 15 mm in depth across the entire rail head, achieving this under field conditions and within a constrained time interval.

**Key words:** laser technologies, laser powder cladding, defect elimination, rail, metallographic analysis, hardness, fatigue strength, cyclic tests.

**DOI:** 10.17580/cisisr.2026.01.07

### Introduction

During operation, due to the cyclic and impact loads, a contact fatigue and a corrosion of metal in the elements of the upper structure of the railway track, the damage occurs, manifested in changes in the size, geometric shape, and condition (chipping, dents, etc.) of the working surfaces [1–5]. The rolling surfaces of the rail head are most susceptible to a wear and mechanical damage [6–9], which can render it inoperable. The ends of the rails and welding joints are particularly susceptible to wear.

The damaged area is removed by cutting out a 10 m long segment of the rail and installing a new one with bolted joints.

This process is not only costly, but also requires time slot with the possible suspension of train traffic. After the replacement, a speed limit is introduced on this section.

Therefore, it is important to develop a technology that allows carrying out repairs under field conditions in order to extend the service life without speed restrictions and in the time intervals between trains movements.

At the same time, the existing production capacities of the rail rolling plants are capable of satisfying only a part of the infrastructure needs for the new rails, making restoration technologies more economically feasible compared to complete replacement [9, 10].

Widely used methods of metal deposition on prepared damaged areas, including automated, partially mechanized, manual electric arc and thermite methods, require strict control of technological parameters to ensure the necessary quality indicators of the deposited layer [11]. Such indicators include the absence of pores and inclusions, the uniformity of the microstructure, the minimum zone of thermal influence, as well as the compatibility of the mechanical properties of the deposited material with the base metal [11–13]. Failure to comply with these requirements reduces the rail's fatigue life, promotes crack development, and increases safety risks for train operations.

In multi-layer cladding, careful cleaning of each surfaced layer is required before surfacing the next one. The poor quality removal of the slag crust, especially when carrying out the work on a road without stopping train traffic, leads to the formation of slag inclusions in the surfaced layer, which leads to cracks. The high thermal effect on the metal of the repaired elements of the upper structure of the railway track causes a decrease in its hardness, which can be a factor in the formation of the damage in a track in the form of changes in the size and the shape of the working surfaces and crushing [14, 15].

These disadvantages highlight the need to develop and implement new repair methods, such as laser powder cladding, to ensure the higher-quality repairs with a minimal impact on the performance characteristics of the track [11–13, 16–19].

The purpose of this work is to study and test the created coating, produced by the method of laser powder cladding of an experimental iron-based powder material with the addition of the alloying elements onto a substrate made of 76KhF rail steel category DT350 (type R65), for compliance with the technical requirements of the regulatory documentation of Russian Railways (OJSC RZhD).

### Materials and methods

The objects of the study and testing are the experimental samples (Fig. 1), which are the railway rails type R65, made of 76KhF steel category DT350 according to GOST R 51685 “Railway rails. General specifications”. The length of the experimental rail samples is 1200 – 1300 mm. The length of the repaired sections is  $\leq 350$  mm, and the depth is  $\leq 15$  mm.

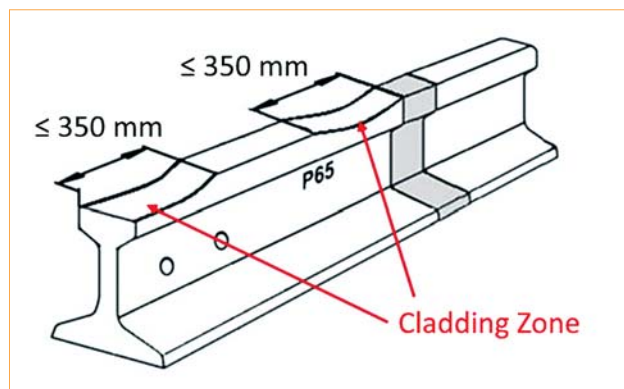


Fig. 1. Sketch of the experimental sample of the railway rails type R65 category DT350

Cladding process was performed on the laser robotic complex of cladding [20], which includes the industrial robot manipulator FANUC M710iC/50, the powder material feed device “Drozd” [21], the IPG LS-4 ytterbium fiber laser with a fiber diameter of 200  $\mu\text{m}$ , and the laser surfacing head with a powder material feeding module on four sides [22]. Surface preparation for cladding is carried out using an abrasive grinding tool in order to prevent the non-metallic inclusions in the surfaced coating [23]. The ranges of the cladding modes: the laser radiation power ( $P$ ) – 2.5–3.0 kW, the laser head speed ( $v$ ) – 7–10 mm/s, the bead overlap step 40–60 % [24], the consumption of a powder material 12–18 g/min. This range was selected based on the preliminary testing of the technological mode.

The experimental iron-based powder material with the addition of the alloying elements (C, Si, Cr, Mn, Ni, S, P) with a granulometric composition of 40–100  $\mu\text{m}$  is used as the filler material.

For the laboratory testing and quality assessment of the cladded metal, the samples of the rails with a repaired damage in the area of the welding joint and the end of the rail were prepared.

Metallographic studies and measurement of the hardness of the metal of the surfaced coating are carried out on the prepared templates. The templates were manufactured using an electrical discharge machining with a constant supply of cutting fluid to the area of the cutting plane. The controlled surface of the template is prepared by a mechanical grinding and polishing with a diamond pastes with a varying grit sizes.

The structure of the surfaced coating metal, the heat-affected zone, the fusion line and the base metal is determined by an etching with the chemical reagents. The surface of the template is etched with the 25 % aqueous solution of nitric acid in the base metal area and aqua regia reagent ( $\text{HCl} + \text{HNO}_3$ ).

Cyclic strength tests are carried out on the BISS 1500 testing machine with a hydraulic pulsator or electrohydraulic power unit equipped with a force meter with a division value of  $\pm 1$  kN and a cycle counter capable of providing a maximum cycle load of 1000 kN [25].

Laser cladding of the experimental samples is performed according to the following scheme:

- preheating of the rails using an induction heater. The optimal temperature regime is selected in the range 380–520  $^{\circ}\text{C}$ , ensuring a rapid heating and maintaining temperature.

- after each weld metal layer, the surface in the laser cladding zone was subjected to deformation hardening using a pneumatic impact hammer. The treatment was performed with a 10 mm diameter hammer head at an impact energy of 7 J and a striking frequency of 3.600 blows per minute. The degree of deformation in the surface layer was defined as the relative change in the thickness of the cladding before and after hardening, amounting to 13 % (calculated using the formula  $\varepsilon = (h_0 - h)/h_0 \times 100\%$ , where  $h_0$  is the layer thickness before hardening and  $h$  is the thickness after hardening; measurements were taken with a micrometer with an accuracy of  $\pm 0.01$  mm). The compaction of the metal extended to a depth of 0.2 mm (determined

by means of transverse sectioning and etching). The surface hardness after hardening, **before subsequent machining**, was 347–370 HV (measured using the Vickers method under a 5 kg load). The rationale for this operation lies in the need to improve the wear resistance of the surface layer through metal densification by work hardening, which results in the formation of a finegrained structure with an increased dislocation density and grain fragmentation. [26, 27].

- laser cladding, carried out sequentially, in the layers using a software for controlling the parameters of the technological process.

- mechanical processing of the clad metal is carried out mechanically using an abrasive tool to restore the geometric dimensions.

### Results and ndiscussion

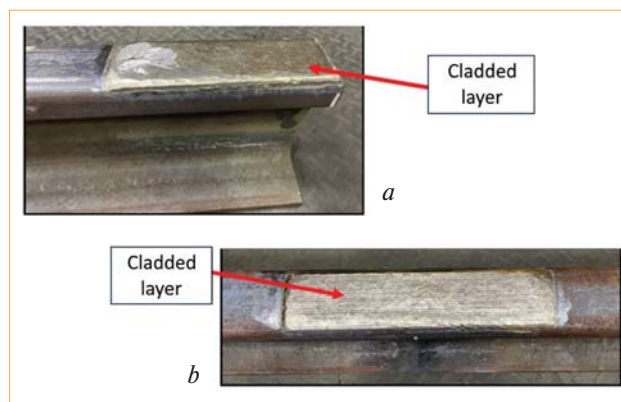
Cladding was performed on the following experimental samples (**Fig. 2**): the one repaired end of the rail and the eight repaired rails with a welding joint in the middle. Of the nine clad rails, seven are subjected to cyclic bending tests. The others are used for metallographic studies.

The characteristics of the clad layer are evaluated according to the parameters presented in the **Table 1**.

During the visual inspection of the experimental samples and the received templates, no defects such as pores, cracks, shrinkage cavities or slag inclusions are found. The maximum thickness of the clad metal was 13–15 mm and the depth of the heat-affected zone (HAZ) was 2.0–2.5 mm. **Fig. 3** shows the images of the longitudinal template of the clad end of the rail and the welding joint of the rail.

Vickers hardness (HV) measurements were carried out at a load of 0.98 N (100 g) with a dwell time of 15 s at 9 points

Table 1. Evaluation criteria for clad rails		
No	Parameter	Value
1	Defects (pores, cracks, slag inclusions)	Absent
2	Hardness of the clad metal, HV	300 – 410
3	Hardness of the metal in the heat-affected zone, HV	≤ 500
4	Conditional fatigue limit of the cladded welding joints, MPa	≥ 171



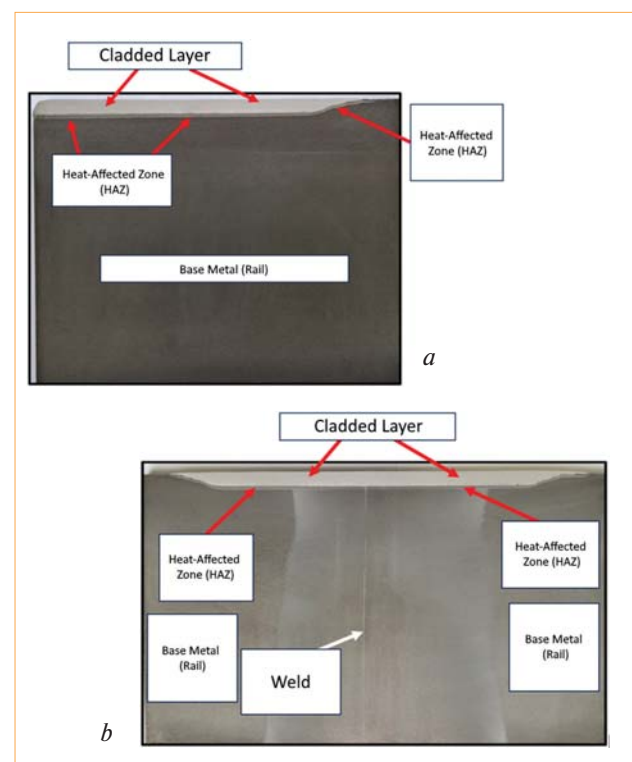
**Fig. 2. Clad rails before a grinding:** *a* – end of the rail; *b* – welding joint

on the transverse section of the sample: in three cladding layers (top, middle, bottom) at three horizontal levels (center, left and right boundaries of the cladding zone). The obtained hardness values of the clad metal **after final machining** varied within the range of 354–376 HV, which is within the permissible regulatory range established for this type of material. In the heat-affected zone, where the structure of the material changes under the influence of a high temperature, the hardness was recorded in the range of 293–308 HV. These values confirm that the laser cladding process did not lead to significant thermal deformations or deterioration of the mechanical properties of the material. No quenched structures with a hardness exceeding 500 HV were detected in the heat-affected zone.

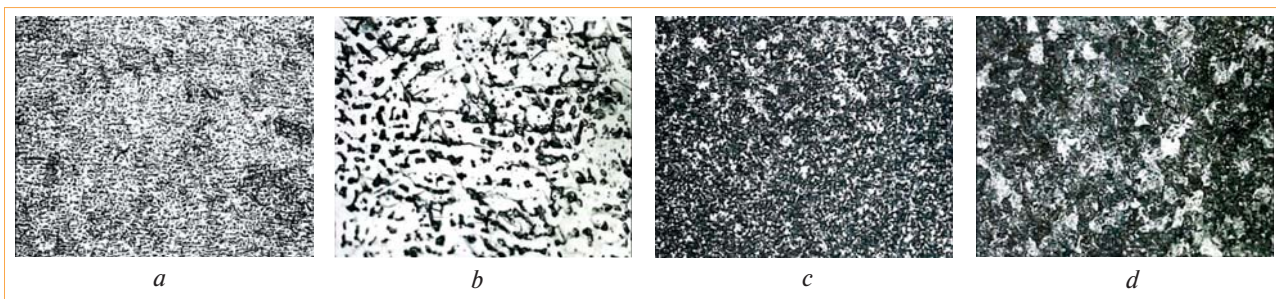
The microstructure of the template of the experimental samples with the clad metal is shown in **Fig. 4 a, b**. It consists of an austenitic matrix with the carbide inclusions located along the boundaries of austenitic grains and within the matrix grains. No defects such as pores, cracks or slag inclusions are found in the clad metal. **Fig. 4 c, d** shows the microstructure of the heat-affected zone. This zone is fine-grained and consists of a fine lamellar pearlite and ferrite.

Based on the results of metallographic studies and hardness measurements of the experimental samples of the rails with the clad metal on the end and the welding joints, it can be concluded that the quality meets the established requirements and is satisfactory.

Spectral analysis of the clad metal, performed using an optical emission spectrometer, confirmed that its composition corresponded to the specifications of the experimental powder. The results of spot X-ray fluorescence (*XRF*)



**Fig. 3. Longitudinal templates of the experimental cladded:** *a* – end of the rail; *b* – welding joint



**Fig. 4. Microstructures of the studied samples:**  
*a* – cladded metal (×100 magnification); *b* – cladded metal (×500 magnification);  
*c* – heat-affected zone (×100 magnification); *d* – heat-affected zone (×500 magnification)

Measurement Point	Fe	C	Si	Cr	Mn	Ni	S	P
1	Bal.	0.570	0.601	24.541	13.209	2.971	0.006	0.031
2	Bal.	0.568	0.658	24.597	13.190	2.989	0.006	0.030
3	Bal.	0.572	0.625	24.511	13.194	2.966	0.005	0.032

analyses taken at the beginning, middle, and end of the repaired section are presented in **Table 2**.

These results show that the measurements at the three points exhibit only minor deviations from one another, confirming the uniform distribution of the alloying elements.

Cyclic tests were carried out according to the scheme shown in the **Fig. 5**. At the first stage, cyclic tests established that the conditional fatigue limit under the cyclic bending loads was 317 MPa. This parameter exceeds the regulatory requirements by 85 %, according to which the minimum endurance limit should be no less than 171 MPa [25].

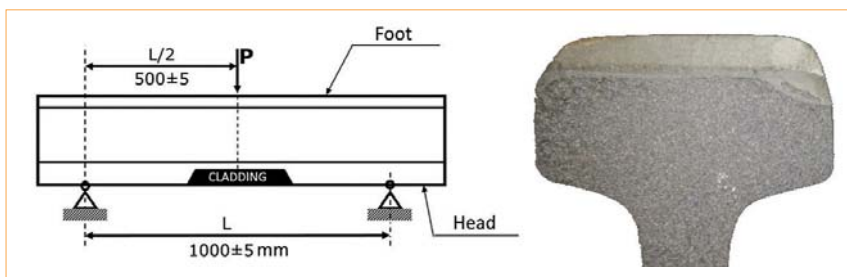
To verify the previously obtained results and confirm the stability of the characteristics, repeated cyclic tests were carried out on three experimental samples. The laser clad-

ding of these samples was performed with adjusted parameters: the laser power range was changed from 2.5–3.0 kW to 2.3–2.8 kW, and the bead overlap step was 45–65 % instead of 40–60 %. **Fig. 5** shows the end face of the destroyed rail after cyclic testing.

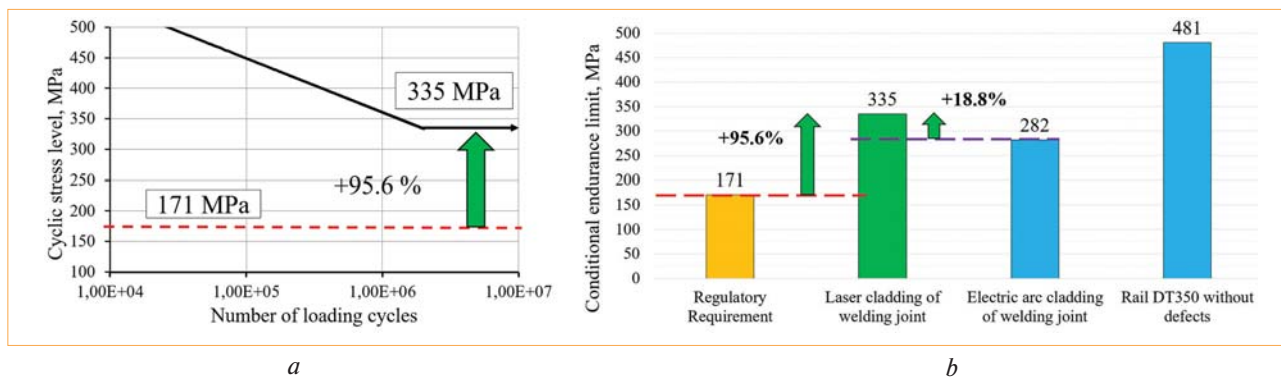
The results showed an increase in the conditional endurance limit to 335 MPa (**Fig. 6, a**).

All experimental samples have the same structure of destruction (**Fig. 5**). Based on the results of cyclic tests, the comparative diagram of the fatigue strength indicators for the two types of cladding was constructed (**Fig. 6, b**).

The increase in fatigue strength after adjusting the parameters is explained by the optimization of the thermal cycle of cladding. The reduction in laser power decreased the



**Fig. 5. Loading scheme and the end face of the destroyed sample**



**Fig. 6. Results of cyclic tests:** *a* – fatigue curve of the cladded welding joints of the rails by laser cladding; *b* – comparative diagram of fatigue strength indicators

proportion of base metal in the clad layer, and the increase in bead overlap changed the nature of the thermal impact on the underlying layers, contributing to a more uniform tempering effect. The combination of these factors, while maintaining the required hardness values (354–378 HV), provided an additional increase in the material's resistance to fatigue failure.

The comparative analysis shows that the samples repaired by laser powder cladding have 18.8% higher fatigue strength than the joints made using electric arc cladding. According to this characteristic, the values obtained after cyclic tests are close to the parameters of a rail without defects. The developed technology allows eliminating the geometric defects and restoring of the functional capabilities of a rail track, ensuring its secondary use with a service life comparable to a new product. The proposed laser cladding technology possesses significant economic potential, despite the high initial cost of the laser equipment. Unlike the traditional method of replacing a rail section longer than 8 m with bolted joints (according to the regulatory documentation of Russian Railways), which is only permissible during a maintenance window of no more than 40 minutes with subsequent speed restrictions, laser cladding does not require prolonged traffic stops on the repaired section. This avoids a significant reduction in the line's carrying capacity, especially on main tracks.

The techno-economic assessment currently being carried out is based on a comparison of: a) capital costs for a mobile laser complex and its maintenance; b) the cost of consumables; and c) avoided losses from train downtime and speed restrictions. Preliminary data confirm that economic losses from train downtime and speed restrictions generally significantly exceed the costs of applying laser cladding technology. Indirect confirmation of economic efficiency is provided by the results of operational tests, which indicate that the service life of restored rails, expressed in terms of passed tonnage, is about 100 million gross tons (according to monitoring data from sections after cladding). This indicator exceeds the initially established in the test methodology (60 mln gross tons) by more than 66 %.

### Conclusion

1. The developed and tested technology of laser powder cladding allowed to eliminate damaged sections of the rails type R65 made of 76KhF steel (category DT350) with a length of up to 350 mm and a depth of defects of up to 15 mm across the entire width of the rail head.

2. Metallographic studies confirmed an absence of the defects (pores, cracks, slag inclusions) in the clad layer and formation of a homogeneous austenitic structure with a carbide inclusions.

3. The hardness of the clad metal on all experimental samples complies with the regulatory requirements: in the clad layer 354–378 HV (with the standard being 300–410 HV); in the heat-affected zone 293–308 HV (with the standard being  $\leq 500$  HV).

4. The quenching structures with a hardness above 500 HV were not detected on the templates.


5. The endurance limit of the experimental samples during cyclic testing exceeded the standard for preliminary

tests by 85 % (317 MPa, at a rate of 171 MPa); for the repeated tests after optimizing the processing mode by 96 % (335 MPa, at a rate of 171 MPa).

6. The comparative analysis showed that the rails repaired by laser cladding of the welding joint demonstrate a higher resistance to the operational loads compared with electric arc cladding and are comparable to the parameters of a rails without defects.

7. The obtained results made it possible to begin conducting a verification test in site on the rails with a length of at least 10 m with repaired sections with a length of no more than 350 mm and a depth of up to 15 mm under conditions of a total load of 60 million gross tons and operation for at least 6 months.

8. The test results will be presented upon the fulfillment of these conditions.

9. Further research is planned in the following areas: determination of the impact toughness of the clad metal and the HAZ; study of the evolution of the microstructure and physical-mechanical properties of rails restored by laser cladding under long-term operational loading; and the development of a detailed techno-economic feasibility study for the implementation of laser cladding technology for the restoration of worn rails. 

*This research is carried out under the order of Russian Railways (OJSC RZhD).*

*The research was carried out within the state assignment in the field of scientific activity of the Ministry of Science and Higher Education of the Russian Federation (theme FZUN-2024-0004, state assignment of the VISU).*

### REFERENCES

- Darenskiy A., Potapov D., Tuley Y., Bugaets N., Malishevskaya A. Revisiting the reasons for contact fatigue defects in rails. *MATEC Web of Conferences*. 2017. Vol. 116. pp. 03001. DOI: 10.1051/mateconf/201711603001.
- Zhang S. Y., Ding H., Lin Q., Liu Q. Y., Spiriyagin M., Wu Q., Wang W. Zhou Z. R. Experimental study on wheel-rail rolling contact fatigue damage starting from surface defects under various operational conditions. *Tribology International*. 2023. Vol. 181. pp. 108324. DOI:10.1016/j.triboint.2023.108324.
- Markov A. A., Antipov A. G., Maksimova E. A. Automation of measurement of butt gaps of a rail track by the magnetic method. *Vestnik nauchno-issledovatel'skogo instituta zheleznodorozhnogo transporta*. 2024. Vol. 83. No. 2. pp. 149–160.
- Skazochkin A. V., Bondarenko G. G., Perov V. B. Investigation of tribological parameters of 76 rail steel modified with ultrafine mineral particles. *Metally*. 2024. No. 4. pp. 75–84.
- Jiang W. J., Liu C., He C. G., Guo J., Wang W. Liu Q. Y. Investigation on impact wear and damage mechanism of railway rail weld joint and rail materials. *Wear*. 2017. Vol. 376–377. pp. 1938–1946. DOI: 10.1016/j.wear.2017.02.035.
- Mishkurov P.N., Rakhmangulov A. N. Typification of industrial railway stations. *Sovremennye problemy transportnogo kompleksa Rossii*. 2012. No. 2. pp. 143–151.
- Torskaya E. V., Tsukanov I. Y., Meshcheryakov A.R., Zagranichnik K.L., Zakharov S. M., Shur E.A. Modeling of contact-fatigue damage of rails in the weld joint area. *Vestnik nauchno-issledovatel'skogo instituta zheleznodorozhnogo transporta*. 2023. Vol. 82. No. 1. pp. 47–57.
- Shevchenko R. A., Yuryev A. B., Kozryev N. A., Mikhno A. R. Patterns of formation of zones with reduced hardness in the welded joint of railway rails. *Metallovedenie I termicheskaya ob-*

- rabotka metallov*. 2022. No. 6. pp. 40–46. DOI: 10.30906/mi-tom.2022.6.40-46.
9. Shcherbakova O. O., Muravyeva T. I., Shkalei I. V. Evolution of the structure and properties of rail steels during operation. *Mashinostroenie: setevoy elektronnyi nauchnyi zhurnal*. 2022. Vol. 9. No. 1. pp. 28–32.
  10. Lu P., Lewis S., Fretwell-Smith S., Engelberg D., Fletcher D., Lewis R. Laser cladding of rail; the effects of depositing material on lower rail grades. *Wear*. 2019. Vol. 438–439. pp. 203045. DOI: 10.1016/j.wear.2019.203045.
  11. Lewis S. R., Lewis R., Fletcher D. I. Assessment of laser cladding as an option for repairing/enhancing rails. *Wear*. 2015. Vol. 330–331. pp. 581–591. DOI: 10.1016/j.wear.2015.02.027.
  12. Tomlinson K., Fletcher D. I., Lewis R. Evaluation of laser cladding as an in-situ repair method on rail steel. *Tribology International*. 2023. Vol. 180. pp. 108210. DOI: 10.1016/j.triboint.2022.108210.
  13. Devoino O. G., Kardapolova M. A., Kalinichenko A. S., Zhar'skiy V. V., Vasilenko A. G. Technology of forming wear-resistant coatings on an iron base by laser processing methods. Minsk: Belarusian National Technical University, 2020. 280 p.
  14. Gudkov A. V., Lozinsky V. N. New technological and technical solutions in the field of welding in railway transport. *Vestnik nauchno-issledovatel'skogo instituta zheleznodorozhnogo transporta*. 2008. No. 6. pp. 3–9.
  15. Dolgoplov B. B., Martyshkin V. I., Volkov A. A. Device for heating a section of rail being restored in transit before electric arc welding. Patent RU 2498539 C1, Russian Federation. MPK H05B 6/10, E01B 31/18. Applied: 2012112266/02, 30.03.2012. Published: 10.11.2013. Bulletin No. 31. 13 p.
  16. Grigoryants A. G., Misyurov A. I., Tretyakov R. S. Analysis of the influence of parameters of coaxial laser surfacing on the formation of rollers. *Tekhnologiya mashinostroeniya*. 2011. No. 11. pp. 19–21.
  17. Grigoryants A. G., Safonov A. N. Methods of surface laser treatment. Moscow: Direct-Media, 2021. 191 p.
  18. Patil M., Acherjee B., Manna I. Enhancing wear resistance of railway wheel by laser surface cladding of martensitic stainless steel on high carbon rail steel. *Materials Today Communications*. 2025. Vol. 42. No. 2. pp. 111353. DOI: 10.1016/j.mtcomm.2024.111353.
  19. Yang K., Zhang T., Zhu Z., Xu L., Lin S., Kou S., Tillmann W. Review of laser cladding coating on wear and fatigue of railway wheels/rails. *Materials Science and Technology*. 2024. Vol. 40. No. 9. pp. 651–664. DOI: 10.1177/02670836241236051.
  20. Gotz A. N., Gusev D. S., Jokin A. V., Zavitkov A. V., Kochuev D. A., Lyukhter A. B., Rodionov D. V., Prokoshev V. G., Chkalov R. V. Device for laser multilayer surfacing of powder materials. Patent RU 202295 U1, Russian Federation. MPK B23K 26/342, B23K 26/144. Applied: 2020129730, 08.09.2020. Published: 10.02.2021. Bulletin No. 4. 6 p.
  21. Lyukhter A. B., Zavitkov A. V., Loktev A. S., Davydov N. N., Kochuev D. A., Kuznetsov M. S., Minin M. V. Powder material feeding device. Patent RU 216688 U1, Russian Federation. MPK B65G 53/14. Applied: 2022127455, 23.10.2022. Published: 21.02.2023. Bulletin No. 6. 25 p.
  22. Lyukhter A. B., Frolov K. A., Kochuev D. A., Zavitkov A. V., Gusev D. S. Distortion of AISI 1020 steel substrate in the process of laser cladding of E-300 powder material. *Journal of Physics: Conference Series. IOP Publishing*. 2021. Vol. 2077. No.1. pp. 012004. DOI: 10/1088/1742-6596/2077/1/012004.
  23. Zavitkov A. V., Loktev A. S., Lyukhter A. B., Frolov K. A. Ways to reduce nonmetallic inclusions in coatings deposited by laser surfacing. *Vestnik Rossiyskogo universiteta druzhby narodov. Seriya: Inzherenye issledovaniya*. 2023. No. 3. pp. 271–278.
  24. Gotz A. N., Gusev D. S., Zavitkov A. V., Kochuev D. A., Lyukhter A. B., Rodionov D. V. Method of laser gas-powder coating of protective coatings. Patent RU 2759102 C1, Russian Federation. MPK B23K 26/342, C23C 26/02. Applied: 2020131465, 28.10.2020. Published: 09.11.2021. Bulletin No. 31. 8 p.
  25. Sukhov A. V., Nikolin A. I., Spashchenko A. A., Lyukhter A. B., Ilyin V. A. Investigation and analysis of qualitative characteristics of deposited elements of the upper structure of the track. *Zheleznodorozhnyi transport*. 2024. No. 10. pp. 45–47.
  26. Fu Y., Zhang H., Wang G., Wang H. Investigation of mechanical properties for hybrid deposition and micro-rolling of bainite steel. *Journal of materials processing technology*. 2017. Vol. 250. pp. 220–227.
  27. Cui Z., Qin Z., Dong P., Mi Y., Gong D., Li W. Microstructure and corrosion properties of FeCoNiCrMn high entropy alloy coatings prepared by high speed laser cladding and ultrasonic surface mechanical rolling treatment. *Materials Letters*. 2020. Vol. 259. pp. 126769. DOI: 10.1016/j.matlet.2019.126769.