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Experimental studies of rail grinding modes using a new high-speed electric drive

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ABSTRACT

Introduction. The operation of rail grinding is used in railway transport as a preventive measure for the formation and development of defects of contact and fatigue origin, wave wear and deformation of transverse profile rails. Currently, JSC Kaluga Plant "Remputmash", together with Siberian State University, is developing a new high-capacity rail train named *PHSP 2.0*. *PHSP 2.0* is 3.5 times more productive than existing analogues. *PHSP 2.0* technology is based on high-speed rail grinding, which requires cutting speed up to 100 m/s. The rotation of grinding wheel is controlled by an electric motor. Today there is no industrial electric drive capable of implementing the required characteristics (7,000 rpm, 45 kW, 60 H·m). **The aim of this work is** to study the modes of rail grinding using a new high-speed electric grinding wheel containing a synchronous electric motor with permanent magnets and frequency converter, which feeds motor with an *AC* voltage with an increased frequency and provides control of the grinding wheel rotation speed. **Research methods.** In order to obtain results of operation of the new electric drive in conditions as close as possible to real-world operating modes and the possibility of implementing high-speed grinding technology, research tests were carried out on a specially designed rail-welding machine. The measurement of grinding wheel speed was carried out by the laser tachometer *"Megeon 18005"*; the assessment of metal removal after mechanical processing was carried out by the profiler rail *PR-03*; the pressure in pneumatic system was measured with pressure transducers of measuring units *VDH 100I-DY1,6-111-0.5*. **Results and discussion.** According to research results, new high-speed electric drive was found to have increased performance due to increased performance and ability to adjust speed of grinding wheel, thus providing the necessary removal of rail head metal with a significant increase in the speed of rail train movement.

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Introduction

Grinding of railway rails is one of the operations for the current maintenance of the track top structure, which forms the rail profile and removes defects that occur during operation. Special rail grinding trains are used for rail grinding. These trains are equipped with abrasive wheels, which process the surface of the rail head according to the flat grinding scheme [1–4].

For the work of rail grinding trains on the railway system, special "technological windows" are organised, when running lines are closed for the movement of any types of rolling stock, which leads to financial losses for transport companies. The organisation of such "windows" is caused by the fact that the speed of a rail grinding train is very low and reaches 4–8 km/h at the grinding wheel rotation speed of 3,600 rpm [5–7]. Therefore, the task of reducing the operating time of a rail grinding train by increasing the operating speed is a priority for the development of the railway industry.

To solve this problem, the *RSHP 2.0* project is being implemented by the *Siberian Transport University* and *Kaluga Remputmash* (*KRPMS*). Within the framework of this project the rail grinding train *RSHP 2.0* is being developed. Its operating speed will be increased up to 15 km/h, while the metal removal rate will remain unchanged at 0.2 mm. In accordance with the previously conducted studies on high-speed rail grinding [8–10] and the theory of cutting [11–13], an increase in the operating speed of the rail grinding train can be achieved by increasing the grinding wheel speed [14].

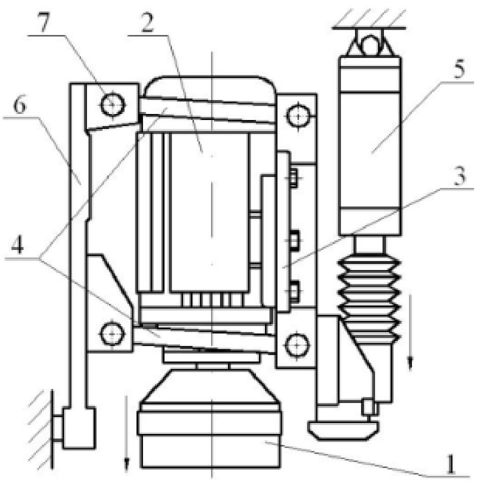

Fig. 1. Grinding head mounting pattern:
1 – abrasive wheel; *2* – electric motor; *3* – motor-mounting plate; *4* – parallelogram suspension; *5* – pneumatic cylinder; *6* – block plate; *7* – axis

Preliminary industrial and laboratory tests [15, 16] have shown the possibility of increasing the working speed of the *RGP 2.0* up to 15 km/h at the grinding wheel rotation speed of 5,000 rpm, and in the future up to 20–30 km/h at 6,000–7,000 rpm. At the same time, the amount of metal removed from the rail remains unchanged and averages 0.2 mm.

Fundamentally, the working equipment of the *RSHP 2.0* does not differ from the used rail grinding trains and is characterised by force closure of the kinematic chain "abrasive wheel - machined surface" [17]. Due to the pneumatic cylinder, grinding wheels are pressed against the surface of the rail head. The pneumatic cylinder acts on the electric motor, which is installed in the lever mechanism of the working equipment (Fig. 1). The pressure in the pneumatic cylinder is regulated depending on the load on the electric motor, which is characterised by the current in the stator. The scheme of controlling the grinding wheel pressure force is shown in Figure 2.

During rail grinding, a certain metal removal should be achieved to obtain the required rail profile. However, grinding with a certain metal removal rate is not possible due to the elastic suspension of the grinding head. In addition, deviations of metal removal from the expected values will lead to violations of the accuracy of the formation of the rail transverse profile [18,19], as well as to changes in the operating conditions of the abrasive tool [20] and deterioration of the quality parameters of the machined surface.

Reducing the difference between the specified metal removal during grinding and obtained can be achieved by establishing empirical dependencies of technological parameters of grinding modes. The main element that determines the modes of grinding is the drive of the grinding wheel, i.e. the electric motor. The characteristics of the electric motor determine the settings of the grinding wheel pressure control system (Fig. 2).

The crucial task in the development of the *RGP 2.0* is the availability of an industrial model of a high-speed electric drive of the grinding wheel with increased shaft speed. During preliminary studies of modes of high-speed rail grinding [15, 16], the required technical characteristics of the high-speed electric drive were determined to ensure the required productivity of the rail grinding train, which are presented in Table 1. In

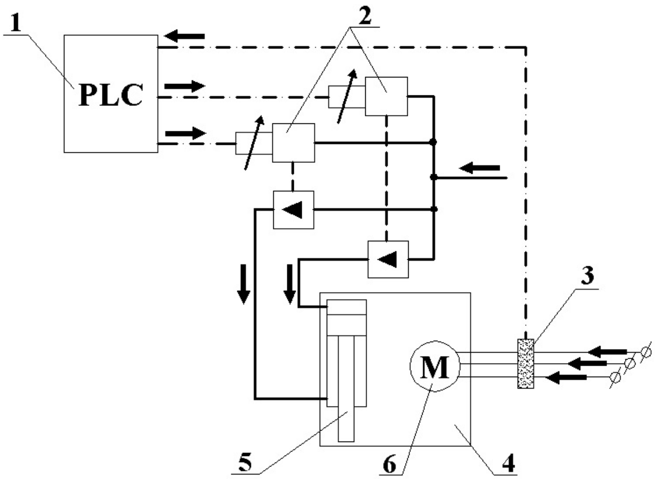

Fig. 2. General pattern for controlling the pressing force of the grinding wheel:

1 – grinding mode control unit; *2* – proportional valve; *3* – converter of the adjusting block; *4* – grinding block; *5* – pneumatic cylinder; *6* – electric motor of the grinding wheel drive

Table 1

Main characteristics of high-speed electric drive

Technical characteristics	Value
Motor shaft speed variable in range, rpm	3,600–7,000
Power at least, kW	45
Torque on the electric motor shaft at least, N·m	60
Overall dimensions: maximum diameter, mm maximum length, mm	 260 580

addition to these technical characteristics, in order to expand the technological capabilities of the new rail grinding train, it is necessary to provide the possibility of adjusting the grinding wheel speed in the design of the new electric drive.

Currently there are no general industrial electric motors with the required technical characteristics, and the creation of a new electric motor is complicated by dimensional limitations associated with the need to place it in the undercarriage space of the rail grinding train. In this connection, *JSC* "*Typhoon*" has designed and manufactured a prototype of a new high-speed electric motor according to the required dimensional parameters.

To make a decision on the application of a new electric drive in the *RGP 2.0*, a set of studies and tests is required to confirm the technical characteristics of the electric motor and its compliance with the required grinding modes.

Statement of research tasks

The main task solved by *JSC* "*Typhoon*" in the development of high-speed electric drive was to improve its performance characteristics due to increased productivity and the possibility of regulating the speed of rotation of the grinding wheel.

This result was achieved by the fact that in the electric drive, including an electric motor that sets the grinding wheel in motion, and a frequency converter that supplies the electric motor with alternating voltage of increased frequency and ensures regulation of the grinding wheel speed, a synchronous motor with permanent magnets of high-speed design with a built-in magnetic field sensor is used as an electric motor, and the frequency converter has an increased carrier frequency and is equipped with high-speed digital control interfaces.

The following advantages of using permanent magnets in the electric motor can be noted in the adopted concept of the new electric drive:

Compactness (reduction of electric motor dimensions by almost 2 times in comparison with general industrial design with the same parameters);

Smooth regulation of the electric motor shaft speed;

Electric motor efficiency is up to 97 % and maximum specific performance.

In accordance with the design documentation of *JSC "Tayfun"* a prototype rail-grinding high-speed electric drive was produced, containing a synchronous motor with permanent magnets as an electric motor (Fig. 3) with the following technical characteristics:

– Rated power – 46.5 kW;

– Nominal speed – 7,000 rpm;

– Nominal parameters of supplying three-phase voltage – 380 V; 233.33 Hz;

– Frequency converter power supply – three-phase input voltage 285–494 V, frequency 50 Hz;

– Output voltage from the frequency converter – three-phase voltage up to 494 V with frequency up to 400 Hz;

– Rated torque on the electric motor shaft – 63.4 N·m;

– Effective value of phase current – 100 A;

– Efficiency – 96 %.

Fig. 3. High-speed electric motor produced by *JSC* "*Typhoon*"

In addition, the electric drive has the possibility of smooth adjustment of the motor shaft speed from 0 to 7,000 rpm. The frequency converter provides output power up to 105 kVA, has a carrier frequency of 8 kHz, withstands continuous current with an effective value of 100 A, is equipped with discrete and analogue inputs and outputs, as well as digital control interfaces *Ethernet*, *RS-485* and *CAN*, and the *CAN* interface is high-speed and has a speed of 250 000 Baud. Starting, stopping, reversing, smooth motor speed control, overload, overheating and short-circuit protection are provided by the frequency converter.

The new high-speed grinding electric motor produced by *JSC* "*Typhoon*" differs fundamentally from the one previously used on rail grinding trains in terms of weight and operating characteristics. In this connection it is required to specify its optimal modes of operation in terms of current loads, which will be determined by the force of grinding wheel pressing against the rail, provided by the appropriate pressure in the pneumatic system. Thus, the main purpose of the research was to set up a new high-speed electric drive and obtain data on its operation under conditions as close as possible to real operating modes.

Research methodology

Research tests of the high-speed electric drive were carried out on an experimental rail grinding unit (*URSH*) [15]. The *URSH* consists of a separate track section 100 m long, standard gauge 1,520 mm (Fig. 4, *a*), on which the rail grinding trolley moves (Fig. 4, *b*). The trolley is driven by a winch-type drive containing a motor, a gear (clutch, brake, single-reduction unit) and a single-layer coiled drum. A *200-kW* diesel generator set is used as a power source. The operation of the *URSH* in the test mode is automatic, monitored by the control system and controlled from a personal computer. To investigate the grinding modes with the new high-speed grinding electric drive, it was mounted on the rail grinding unit *URSH* (Fig. 4, *c*, *d*).

Fig. 4. Overview of the rail grinding unit (the *URSH*):
a – section of railway track; *b* – rail grinding trolley; *c* – high-speed electric motor of JSC "Typhoon"; *d* – frequency converter of JSC "Typhoon"

The grinding wheel is pressed against the machined surface of the rail based on the pressure difference in the rod and piston cavities of the pneumatic cylinder. Adjustment of pressure in the cavities of the pneumatic cylinder was adjusted by a proportional pressure regulator based on the data on the current load in the windings of the high-speed electric motor in accordance with the pattern shown in Figure 2.

The following measuring and control tools were used in testing the high-speed electric drive: the grinding wheel rotation speed was measured using a "*Megeon 18005*" laser tachometer; metal removal after mechanical processing was assessed using a *PR-03* rail profilograph; the pressure in the pneumatic system was measured using *OWEN PD100I-DI1.6-111-0.5* pressure measuring transducers.

Specially designed high-speed rail grinding wheels *PP 35-250×75×150ZK125VT* manufactured by "*Experimental Plant Metallist-Remputmash*" designed for operating speeds up to 100 m/s were used in the research [21].

The research of the new high-speed electric drive for the realization of high-speed rail grinding technology was carried out in the following sequence:

1. The air pressure of 0.5 atm was set in the pneumatic system for pressing the grinding wheel to the rail.
2. At the specified pressure, three grinding passes were made in each of the following grinding modes:
– speed 15 km/h at a grinding wheel rotation speed of 5,000 rpm;
– speed 20 km/h at a grinding wheel rotation speed of 6,000 rpm;
– speed 30 km/h at a grinding wheel rotation speed of 7,000 rpm.
3. During the grinding process, the current load readings on the stator windings of the grinding wheel were recorded.
4. After each pass, the transverse profile of the rails was measured with the evaluation of metal removed from the rail and determination of the average value of removed metal based on the results of three passes.
5. After changing the air pressure in the pneumatic system of pressing the grinding wheel to the rail, points 2–4 were repeated. The following pressure values in the pneumatic system were set during the tests: 0.5; 0.8; 1.0; 1.2; 1.5; 1.8; 2.0; 2.5; 2.8; 3 and 3.5 atm.

Results and its discussion

The summarized results of the study of high-speed electric drive operation modes are shown in Table 2.

Based on the measurement results (Table 2), the dependences of changes in the average values of metal removed from the rail head depending on the current load in the stator windings of the high-speed electric motor are established, which are presented in Figure 5.

The graphs (Fig. 5) show that there is a tendency for metal removal to increase with increasing current load in the electric motor windings to certain values, after which the metal removal values begins to decrease. This pattern is characteristic for all investigated modes of grinding. It can be assumed that such dependence characterizes the efficiency of abrasive tool operation with the established grinding modes. So, the minimum current load is characterized by an insignificant pressure force of the grinding wheel to the rail. This leads to insufficient embedding of abrasive grains into the machined surface with the formation of chips of minimum cross-section and gradual blunting of abrasive grains at minimum cutting forces.

Table 2

Results of a study of the operating modes of a high-speed electric drive

Pressure in the pneumatic cylinder (pressing force), atm	Grinding modes					
	15 km/h (5,000 rpm)		20 km/h (6,000 rpm)		30 km/h (7,000 rpm)	
	Current load, A	Average value of removed metal, mm	Current load, A	Average value of removed metal, mm	Current load, A	Average value of removed metal, mm
0.5	72	0.15	78	0.11	74	0.10
0.8	86	0.21	81	0.12	82	0.11
1.0	94	0.26	91	0.21	86	0.15
1.2	102	0.33	95	0.22	96	0.21
1.5	105	0.35	101	0.30	99	0.24
1.8	115	0.20	103	0.32	104	0.17
2.0	119	0.19	110	0.20	106	0.14
2.5	123	0.19	115	0.18	110	0.12
2.8	131	0.12	125	0.14	115	0.10
3.0	140	0.10	130	0.10	125	0.05
3.5	140	0.10	140	0.05	130	0.03

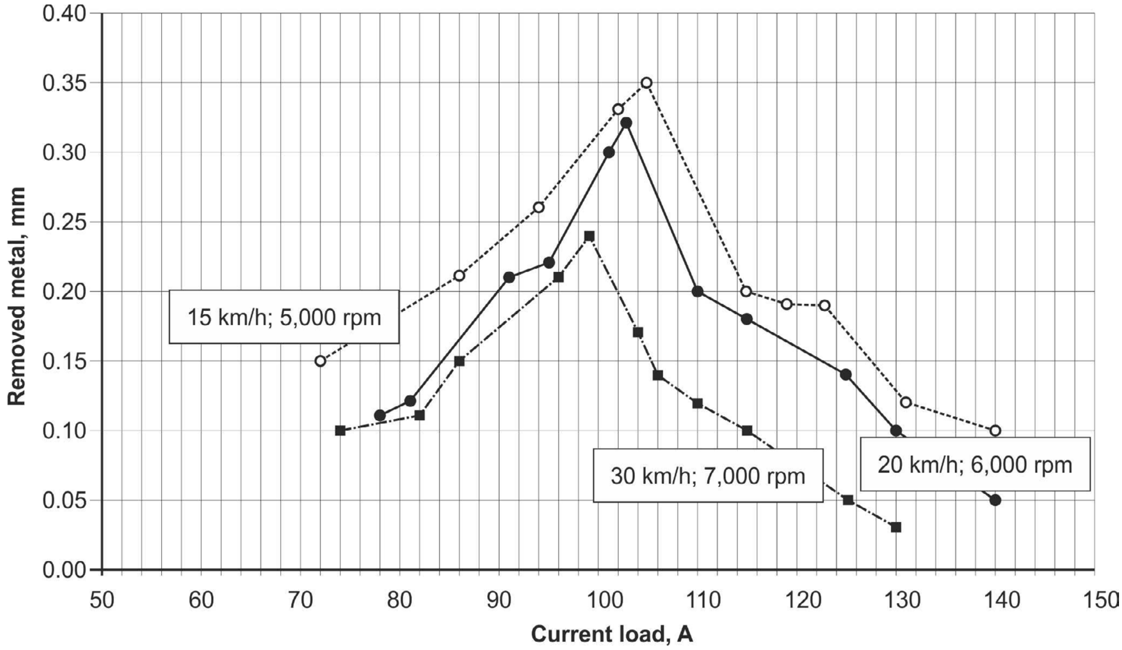

Fig. 5. Average values of metal removal at different current loads on windings of high-speed motor stator

In this case, the forces acting on a single abrasive grain are not enough to renew the abrasive grains, and consequently there is greasing of the grinding wheel surface. In this case, the minimum metal removal is observed, which is 0.1–0.15 mm depending on the modes.

The increasing grinding wheel pressure, which is characterized by an increase in the current load of the motor, leads to a reduction in the influence of the wheel clogging effect. The dulled abrasive grains begin to renew themselves more actively with sharper grains, which provide greater metal removal. The graph shows that at peak points the metal removal reaches values of 0.28–0.35 mm depending on the grinding modes.

A further increase in the grinding wheel load leads to a significant increase in the cutting forces, which significantly exceed the retention forces of the abrasive grains in the bond. This leads to the abrasive grains breaking out without chip removal. At the same time there is a decrease in metal removal down to minimum values of 0.03–0.1 mm.

Thus, the extrema on the presented graphs (Fig. 5) characterize the maximum cutting ability of grinding wheels, and these values can be accepted as the optimal modes of operation of abrasive tools.

The highest metal removal value of about 0.35 mm is provided at a grinding speed of 15 km/h. When the grinding speed increases to more than 15 km/h, a decrease in metal removal and a reduction in current load values are observed. So, at 15 km/h and 5,000 rpm, the maximum metal removal value is achieved with a current load of 105–110 A, and at 30 km/h and 7,000 rpm the maximum metal removal value is achieved with a current load of 95–100 A. This indicates that each grinding speed corresponds to its own required value of the grinding wheel pressing force to the rail to ensure optimum cutting forces.

Taking into account the effective value of phase current for the new high-speed electric drive (100 A), the possible metal removal at different grinding modes and its optimal values were determined and are presented in Table 3.

To ensure the motor current loads specified in Table 3, it is necessary to ensure the appropriate grinding wheel-to-rail pressure depending on the grinding conditions. The required grinding wheel-to-rail pressure is shown in Figure 6.

The graphs (Fig. 6) show that with the operating range of current loads of the new high-speed electric drive of 90–100 A, depending on the grinding speeds, it is required to ensure the pressure in the pneumatic system for pressing the grinding wheel to the rail within the range of 0.7–1.8 atm.

Table 3

Current loads of electric motor to allow metal to ensure the required metal removal at different grinding speeds

Grinding speed, km/h at grinding wheel speed	Metal removal, mm				
	0.15	0.2	0.25	0.3	0.35
15 (5,000 rpm)	70–75 A	80–85A	90–95 A	95–100 A	105–110 A
20 (6,000 rpm)	80–85 A	85–90 A	95–100 A	100–105 A	–
30 (7,000 rpm)	85–90 A	90–95 A	–	–	–

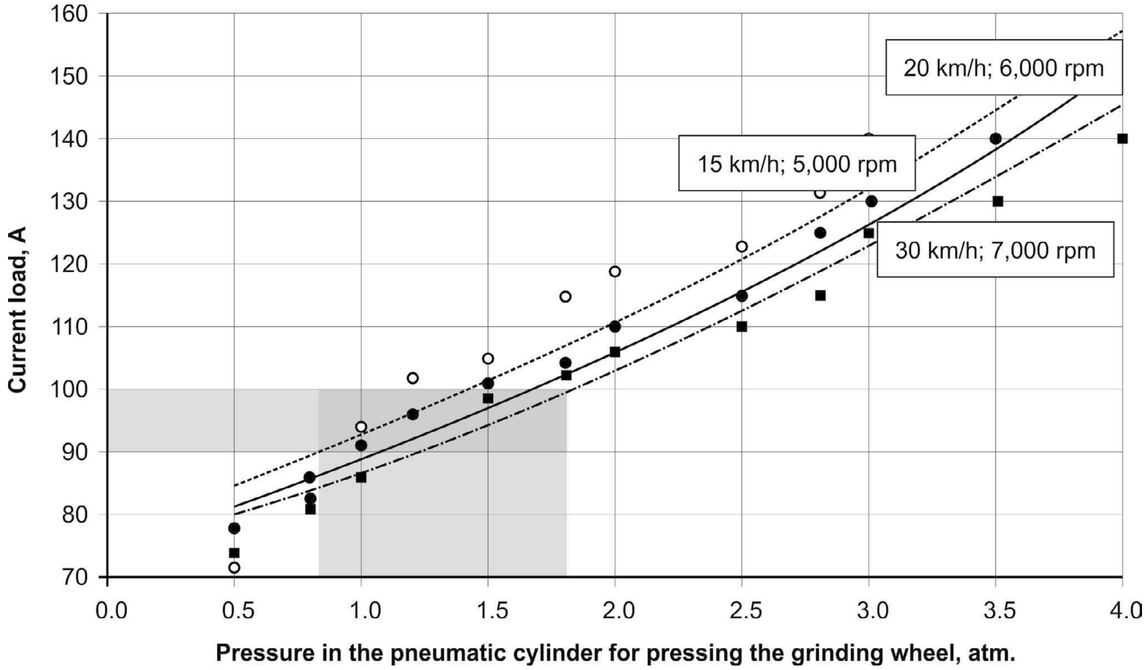

Fig. 6. Average values of current load of electric motor at different pressure in the pneumatic system

The obtained values of the optimal parameters of the pressure of pressing the grinding wheel to the rail and the current loads of the electric motor allow determining the required parameters and characteristics of the pneumatic drive of the grinding head and electrical systems when designing a new rail grinding train, which allows implementing the required grinding modes to ensure a specified metal removal from the rail.

Conclusions

According to the results of the conducted tests of rail grinding modes with the use of a new high-speed electric drive of grinding wheel, the following conclusions can be drawn:

1. The new high-speed rail grinding electric drive has improved performance characteristics due to increased productivity and possibility to regulate the grinding wheel speed, which ensures the required metal removal from the rail head with a significant increase in the speed of the rail grinding train. The high-speed electric drive is efficient and operates under the loads specified in the technical specifications for the electric drive with the required torques and speeds.

2. In the high-speed electric drive, the frequency converter maintains the rotation of the electric motor shaft with a constant torque at a rotation speed of 5,000–7,000 rpm and a speed of the rail grinding train

of 15–30 km/h, thus ensuring the removal of metal with a thickness of 0.2–0.3 mm at increased operating speeds.

3. The electric motor shaft rotates steadily, evenly, without seizures and noises in all grinding modes. The electric motor withstands the radial shaft load (up to 3 kN) distributed along the length of the output end of the shaft and the axial shaft load up to 3 kN.

4. The optimum current loads of operation of the high-speed electric motor depending on the grinding speed are established.

5. The values of pressure in the pneumatic system of pressing the grinding wheel to the rail to ensure optimal current loads are established.

6. The research results will be used in the design of rail grinding train *RSHP 2.0*, which implements high-speed grinding technology.

References

1. Funke H. *Rail grinding*. Berlin, Transpress, 1986. 153 p.

2. Fan W., Liu Y., Li J. Development status and prospect of rail grinding technology for high speed railway. *Journal of Mechanical Engineering*, 2018, vol. 54 (22), pp. 184–193. DOI: 10.3901/JME.2018.22.184.

3. Schoch W. Grinding of rails on high-speed railway lines: a matter of great importance. *Rail Engineering International*, 2007, vol. 36 (1), pp. 6–8.

4. Abdurashitov A.Yu., Sukhov V.V. Vliyanie ispol'zovaniya rel'soshlifoval'nykh poezdov na prodlenie zhiznennogo tsikla rel'sa [The impact of the use of rail-grinding trains on the prolongation of the rail life cycle]. *Put' i putevoe khozyaistvo = Railway Track and Facilities*, 2023, no. 8, pp. 20–22.

5. Suslov A.G., Bishutin S.G., Zakharov L.A. Innovatsionnye tekhnologii rel'soobrabotki vysokoskorostnykh zheleznykh dorog [Innovation technologies of rail working for high-speed railways]. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2020, no. 8, pp. 11–17. DOI: 10.30987/2223-4608-2020-8-11-17.

6. Verma S., Joseph Selvi B., Yogesh Shah V. Influence of rail grinding operations on the World's Largest Multimodal Network. *International Conference on Advances in Design, Materials, Manufacturing and Surface Engineering for Mobility. SAE Technical Paper*. SAE International, 2022. DOI: 10.4271/2022-28-0560.

7. Liu P., Zou W., Peng J., Xiao F. Investigating the effect of grinding time on high-speed grinding of rails by a passive grinding test machine. *Micromachines*, 2022, vol. 1, p. 2118. DOI: 10.3390/mi13122118.

8. Ilyinykh A.S. Skorostnoe shlifovanie rel'sov v puti [Speed rail grinding]. *Mir transporta = World of Transport and Transportation*, 2011, no. 3, pp. 56–61.

9. Khvostikov A.S. Povyshenie effektivnosti skorostnogo shlifovaniya rel'sov v puti [Improving the efficiency of high-speed grinding of rails in transit]. *Sovremennye naukoemkie tehnologii = Modern High Technologies*, 2023, no. 5, pp. 30–35.

10. Taubert M., Pyushel' A. Skorostnoe shlifovanie rel'sov [High-speed grinding of rails]. *Zheleznye dorogi mira*, 2010, no. 7, pp. 31–33. (In Russian).

11. Zenga W., Lib Z., Peib Z., Treadwell C. Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics. *International Journal of Machine Tools and Manufacture*, 2005, vol. 45 (12–13), pp. 1468–1473.

12. Doman D., Warkentin A., Bauer R. A survey of recent grinding wheel topography models. *International Journal of Machine Tools and Manufacture*, 2006, vol. 46, pp. 343–352. DOI: 10.1016/j.ijmachtools.2005.05.013.

13. Ostrovskii V.I. *Teoreticheskie osnovy protsessa shlifovaniya* [Theoretical basis of the grinding process]. Leningrad, LGU Publ., 1981. 143 p.

14. Koshin A.A., Chaplygin B.A., Isakov D.V. Adequacy of the operating conditions of abrasive grains. *Russian Engineering Research*, 2011, vol. 31 (12), pp. 1221–1226.

15. Ilinykh A.S., Pikalov A.S., Miloradovich V.K., Galay M.S. Experimental studies of high-speed grinding rails modes. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2023, vol. 25, no. 3, pp. 19–35. DOI: 10.17212/1994-6309-2023-25.3-19-35. (In Russian).

16. Ilinykh A.S., Pikalov A.S., Galay M.S., Miloradovich V.K. Povyshenie proizvoditel'nosti rel'soshlifoval'nykh poezdov metodom skorostnogo shlifovaniya [Increasing the performance of rail grinding trains by the method of speed grinding]. *Izvestiya vysshikh uchebnykh zavedenii. Severo-Kavkazskii region. Tekhnicheskie nauki =*

University News. North-Caucasian Region. Technical Sciences Series, 2022, no. 4 (216), pp. 46–56. DOI: 10.17213/15603644202244656.

17. Aksenov V.A., Ilinykh A.S., Galay M.S. Matafonov A.V. Osobennosti formirovaniya tekhnologicheskogo protsessa ploskogo shlifovaniya tortsom kruga pri uprugoi podveske shlifoval'noi golovki [Features of formation of the fl at grinding technological process by an end face of a circle with an elastic suspension grinding head]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Mashinostroenie, materialovedenie = Bulletin PNRPU. Mechanical engineering, materials science*, 2016, vol. 18, no. 4, pp. 34–47. DOI: 10.15593/2224-9877/2016.4.03.

18. Mesaritis M., Shamsa M., Cuervo P., Santa J., Toro A., Marshall M., Lewis R. A laboratory demonstration of rail grinding and analysis of running roughness and wear. *Wear*, 2020, vol. 456–457. DOI: 10.1016/j.wear.2020.203379.

19. Satoh Y., Iwafuchi K. Effect of rail grinding on rolling contact fatigue in railway rail used in conventional line in Japan. *Wear*, 2008, vol. 265 (9–10), pp. 1342–1348. DOI: 10.1016/j.wear.2008.02.036.

20. Zhou K., Ding H., Zhang S., Guo J., Liu Q., Wang W. Modelling and simulation of the grinding force in rail grinding that considers the swing angle of the grinding stone. *Tribology International*, 2019, vol. 137, pp. 274–288. DOI: 10.1016/j.triboint.2019.05.012.

21. Ilinykh A.S., Miloradovich V.K., Galay M.S. Issledovanie vliyaniya komponentov abrazivnogo instrumenta na ego ekspluatatsionnye svoistva pri skorostnom shlifovanii rel'sov [Study of influence of abrasive tool components on operational properties for high-speed rail grinding]. *Izvestiya vysshikh uchebnykh zavedenii. Severo-Kavkazskii region. Tekhnicheskie nauki = Bulletin of Higher Educational Institutions. North Caucasus Region. Technical Sciences*, 2023, no. 3, pp. 28-37. DOI: 10.17213/1560-3644-2023-3-28-37.

Conflicts of Interest

The authors declare no conflict of interest.