

Keywords: clutch; wheel; rail; magnetization; sand; scale; magnetite

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ELECTROMAGNETIC SYSTEM FOR IMPROVING THE ADHESION OF WHEELS TO RAILS

Summary. The article describes the design of a system used for the improvement of the adhesion of locomotive wheels to rails; the principle of which is based on the electromagnetic feeding of the contact area with the bulk material that has magnetic properties and high hardness (iron scale Fe_3O_4 and magnetite $\text{FeO}\cdot\text{Fe}_2\text{O}_3$). The experimental results of laboratory and bench tests confirming the effectiveness of the proposed system compared with the existing devices using quartz sand to improve the adhesion of wheels to rails are presented. It is concluded that the use of an electromagnetic system for improving the particle supply to the wheel/rail interface is promising.

1. INTRODUCTION

The operation of many heavily loaded rolling friction pairs is maintained under conditions, by presenting hard particles of different origin in the zone of their contact. These particles may be either products of wear of contacting surfaces or various foreign bodies, often of mineral origin, which is sometimes artificially fed into the contact area [1-4].

The pulling force strongly depends on the climatic influences, which causes loss of adhesion, and this can lead to slippage of wheels and damage to the wheels and rails [5]. The presence of a third body between wheel and rail significantly affects the adhesion. Poor adhesion of the wheels to rails can cause various problems, such as high-frequency noise [6], fatigue of the contact surface [7], increased corrugation of rails [8], energy dissipation [9], unstable adhesion before acceleration [10], and poor braking performance [11].

Traditionally, sand is used to increase the coefficient of adhesion of locomotive wheels to rails. This method has widespread usage in railway transportation; however, it has significant limitations, the main ones of which are [12-14]:

- low efficiency (the ratio of the amount of sand placed between the wheel and the rail to the total amount of sand directed under the wheel of the locomotive);
- the use of large volumes of sand in the rolling stock, leading to clogging of the rail tracks, which causes environmental problems; and
- increased wear of the working surfaces of wheels with rails.

One way to solve this problem is the use of alternative sand bulk materials [4]. As the latter, it is proposed to use abrasive materials having magnetic properties [15-18], for example, magnetite (FeFe_2O_4), which is the iron oxide of natural origin, and iron scale (FeOFe_2O_3), which is a by-product of foundry and forging. These materials are similar to quartz sand in terms of hardness.

In this regard, the study of the use of magnetite and iron scale in order to increase the coefficient of adhesion of locomotive wheels to rails is a task of current interest.

2. MAGNETIC PROPERTIES OF WHEEL AND RAIL MATERIALS

Magnetic properties of abrasive materials and wheel and rail materials ensure a reliable retention of abrasive loose material on the working surfaces, as well as its uniform distribution in the friction contact zone.

It was shown in [19 - 22] that the steel used for the production of rails and bands has satisfactory magnetic properties (residual induction 0.65 ... 0.87 T, coercive force 898 ... 963 A/m), which enables holding of particles of abrasive loose material on working surfaces.

With local magnetization of the working surfaces, a relatively small volume of material must be brought to saturation, since the average value of the nominal contact area between the wheels and rails is about $1 \cdot 10^{-4} \text{ m}^2$ [21].

Fig. 1 shows the amplitude variation graphs of the horizontal (H_x) and vertical (H_y) components of the magnetic field, depending on the depth of magnetization by magnets of different types [20]. For the rod-type magnets, the schematic model with the designation of the main geometric dimensions (2Δ is the width of the magnet pole) is given. The abscissa axis lies in the same plane as the magnetized surface.

Dependencies shown in Fig. 1 correspond to the case when the gap between the magnet pole and the magnetized surface is zero. The values of the component of the magnetic field of the rod magnet H_x , constructed in dependence on the magnitude of this gap, are shown in Fig. 2.

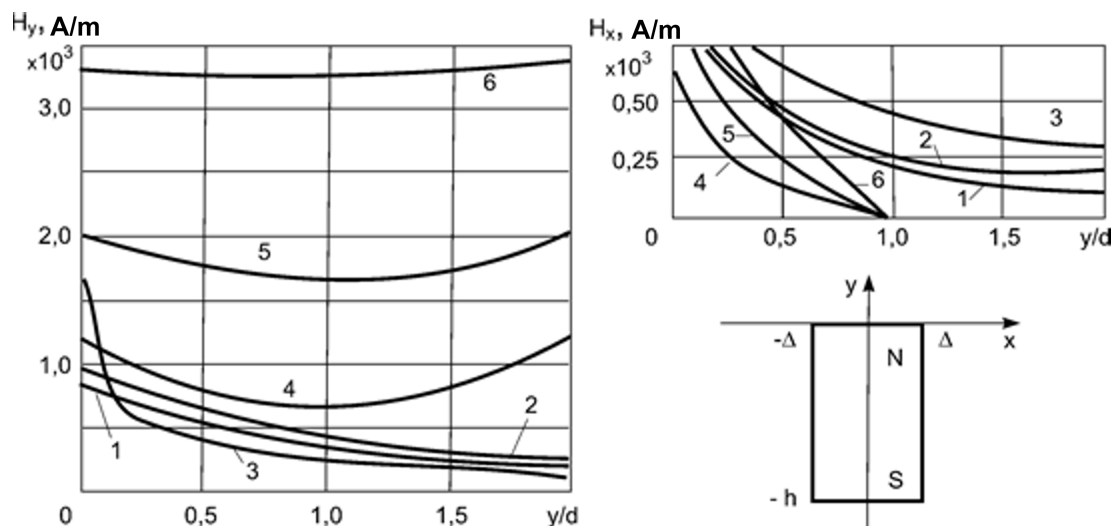


Fig. 1. The change in the compound amplitudes of the magnetic field as a function of the depth of magnetization by magnets of various types: 1 – bar magnet $h = 6\Delta$; 2 – bar magnet $c h \rightarrow \infty$; 3 – annular magnet; and 4, 5, 6 – Π -shaped magnets with $d = 3\Delta$, $d = \Delta$, $d = \Delta / 3$, respectively

In view of the foregoing observation, to magnetize the working surfaces of the wheels with the rails, it is sufficient to use an electromagnet that creates magnetic fields with a strength of 500–650 A/m. This electromagnet is oriented by one of its poles perpendicular to the rolling surface, while the magnetic field lines create a locally magnetized unipolar zone.

In the process of magnetization (or demagnetization) of the wheel and rail surfaces, the electromagnet can work both in pulsed and continuous modes, which is determined by external conditions affecting the state of the frictional contact of the wheel with the rail and the mode of operation of the rolling train.

The gap between the electromagnet pole and the rolling surface of the rail, taking into account the movement of the carriage relative to the rail, is 40–50 mm for maintaining the necessary magnetic field strength (averaged values for the rolling train of different types). In the case of magnetization of the wheel circle, the gap is smaller (15–20 mm) and determined for the safe operating reasons of the device.

For using in these purposes, a rod magnet is preferred that is simple in design and has satisfactory magnetic characteristics necessary to magnetize rolling surfaces with the required magnetic field density.

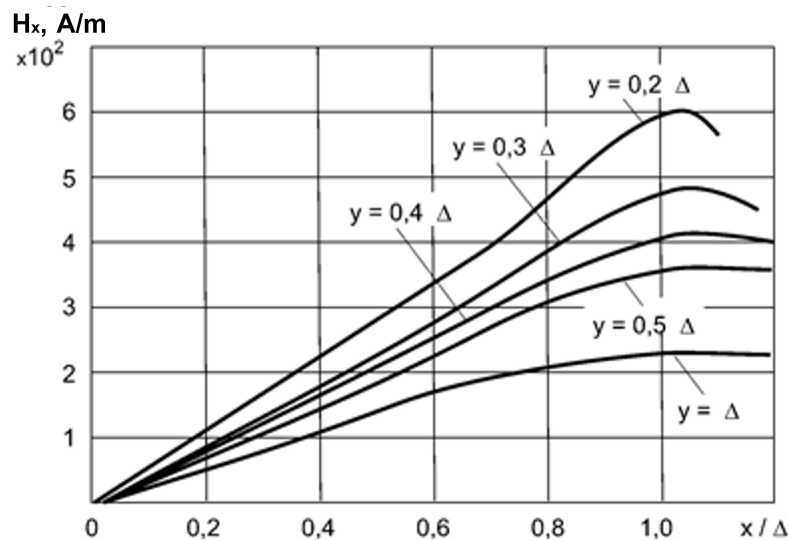


Fig. 2. Dependences of the component H_x of the residual magnetic field at various distances from the pole of the rod magnet to the magnetized surface

3. CONSTRUCTION AND PRINCIPLE OF THE NEW SYSTEM OF WHEELS TO RAILS CLUTCHING IMPROVEMENT

To supply magnetic bulk material under the wheel of the locomotive by magnetic forces, a system is developed, and its scheme is shown in Fig. 3. This system is protected by the patent of Ukraine [23]. The structure consists of three electromagnets 6 and a permanent magnet 9, located on the duct 7 for the supply of bulk material. The duct 7 is connected at one end to the hopper 3 and at the other end to the duct 8, through which compressed air is supplied. The design also includes two electromagnets 4 and 5, located at some distance from the surfaces of the wheel and rail, respectively. To control the operation of the system, an appropriate electronic unit 10 is provided.

The system works as follows. If it is necessary to improve the adhesion, the control unit 10 simultaneously sends electrical signals to the compressed air control (not shown in Figure 1) and electrical current pulses to the electromagnet system 6. The electrical signals can be fed either automatically (from the sensor) or directly by the driver.

In this case, electromagnets 6, turning-on in turn, create a moving magnetic field transporting a predetermined amount of the working bulk material along the duct 7 and further into the duct 8, where, under the influence of compressed air, it enters the contact area between the wheel 1 and the rail 2. In the general case, the algorithm for generating control pulses depends on the mode of operation of the railway rolling train, its speed, the state of the working surfaces of the wheels with rails, weather conditions, and other factors.

In the immediate vicinity of the wheel 1 and the rail 2 are placed electromagnets 4 and 5, which serve to magnetize their working surfaces. Due to this, the magnetized particles of the abrasive material adhere and remain for some time on the working surfaces.

The permanent magnet 9 serves to prevent the spontaneous introduction of the working bulk material from the hopper 3 into the spout 8 (for example, in the case of de-energizing the electromagnet system 6). In this case, the permanent magnet 9 has several times less power than the system of electromagnets 6 and is not able to prevent the movement of the working bulk material caused by it through the duct 7.

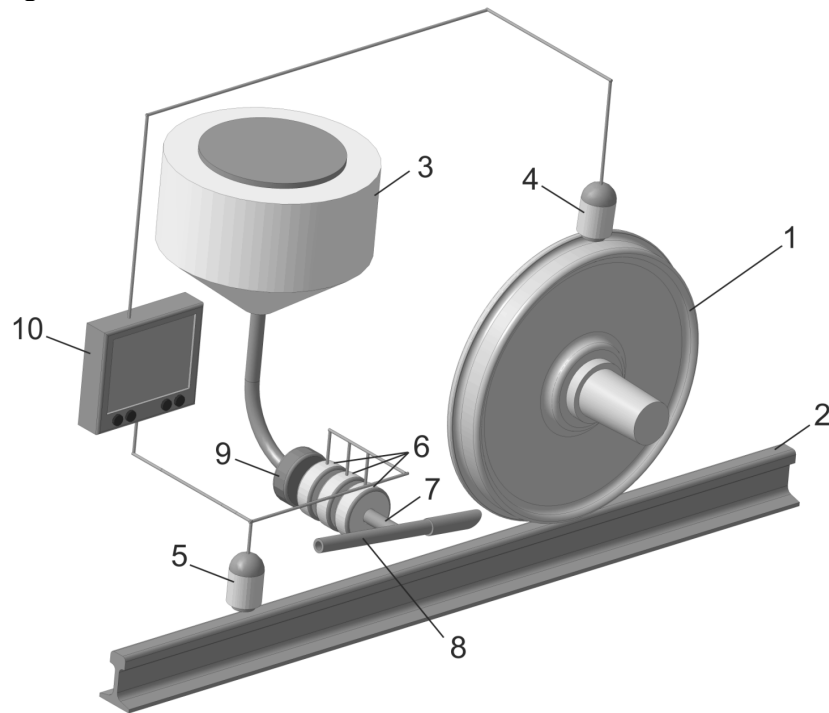


Fig. 3. Scheme of the electromagnetic system used for improving the adhesion of wheels to rails: 1 - wheel; 2 - rail; 3 - hopper for bulk material; 4, 5, 6 - electromagnets; 7 - duct for the supply of bulk material; 8 - duct for supplying compressed air; 9 - permanent magnet; and 10 - control unit

4. STUDY OF WORKING CHARACTERISTICS OF THE ELECTROMAGNETIC CLUTCH IMPROVEMENT SYSTEM

Tests of the electromagnetic feed system used for improving the clutching of wheels to rails were carried out on a field stand consisting of two independent wheeled vehicles, one of which was mounted on the wheelsets of the other, using them as rollers [24]. One of the wheelsets was rotated by an electric motor by means of a belt drive.

During the laboratory and bench tests, it was found that the developed electromagnetic feed system allows the assurance of stable transportation of working material (iron scales or magnetite) and its relatively uniform distribution on a magnetized surface over a wide range of flow rates (for internal diameter of the supply pipeline 10 mm, the productivity may vary smoothly from 0.08 kg/min to 0.47 kg/min). At the same time, the losses of the working bulk material are insignificant. The ratio of the mass of the working material (grain size 100–200 μm) fixed on the surface of the bandage to the material fed by the electromagnetic system is 0.93 (iron scale) and 0.97 (magnetite).

The electromagnetic feed system of the working material makes it possible to ensure its stable feeding with the required capacity. In this case, the deviation of the flow values from the set value does not exceed 2–4%.

The verification results of reproducibility of the bulk material consumption rate G values at different electromagnetic feed system performances are shown in Table 1.

Table 1

Reproducibility of the bulk material consumption rate values of the electromagnetic system for improving the adhesion of wheels to rails

G, kg/min	Statistical characteristics, kg/min	
	0.08	$F_G\sigma$
ΔF_G		0.009
0.16	$F_G\sigma$	0.026
	ΔF_G	0.016
0.26	$F_G\sigma$	0.029
	ΔF_G	0.018
0.33	$F_G\sigma$	0.034
	ΔF_G	0.021

G – bulk material consumption rate;

ΔF_G – confidence limits (confidence figure $\alpha = 0.95$);

$F_G\sigma$ – mean standard deviation.

The time parameters characterizing the work of the electromagnets transporting the working material (set by the control unit) were also identical. The duration of operation of the first, second, and third transporting electromagnets (during the movement of the working bulk material in duct 7 (see Figure 3) was 10 ms (during the operating cycle). The pause between switching on the second electromagnet and the beginning of the operating cycle was 10 ms. The pause between switching on the third electromagnet and the beginning of the operating cycle was 20 ms. The first transporting electromagnet was switched on immediately after the start of the operating cycle.

The performance of the electromagnetic supply system was controlled by changing the delay time between two subsequent operating cycles, which ranged 50–200 ms. A smaller pause value corresponds to a larger system performance.

The above electromagnetic system used for improving the adhesion of the locomotive wheel to the rail has the following main characteristics:

- Number of control ducts (electromagnet system 6 in figure 3): 3;
- Maximum current consumed by the electromagnet: 40 A;
- The initial voltage applied to the electromagnet: 40 V;
- Minimum resistance of the duct with an electromagnet: 1 Ohm;
- Discreteness of regulation of time parameters of the operating cycle: 0.1 ms;
- Duration of the operating cycle: 0,1–1000 ms;
- Duration of a pause between operating impulses of an electromagnet: 0,1–1000 ms; and
- The duration of the operating pulse of an electromagnet: 0.1–1000 ms;

5. THE EFFICIENCY VERIFICATION OF THE PROPOSED SYSTEM IN COMPARISON WITH ANALOGUES USING QUARTZ SAND

A series of experiments was carried out to measure the adhesion factor of interacting surfaces of the wheels with rails in order to verify the effectiveness of the wheel-to-rail adhesion when using bulk materials with electromagnetic properties and high hardness.

The experiments were performed on a full-scale bench unit that allowed the reproduction of the force interaction conditions between the wheels and rails in the real scale of forces, time, geometric

dimensions, heat fluxes, and the physicochemical state of the contacting surfaces [25]. The basis of the stand was a railroad rail of a P-65 brand, a railway wheel of a 0.525 m radius, and a strength load system.

Quartz sand, iron scale (Fe_3O_4), which is a by-product of rolling and forging production and iron oxide, and magnetite ($\text{FeO}\cdot\text{Fe}_2\text{O}_3$), which is of natural origin, were used as bulk materials. The distribution density of bulk materials on the rail surface was 0.02 g/cm^2 . The results of the experiments are shown in Fig. 4.

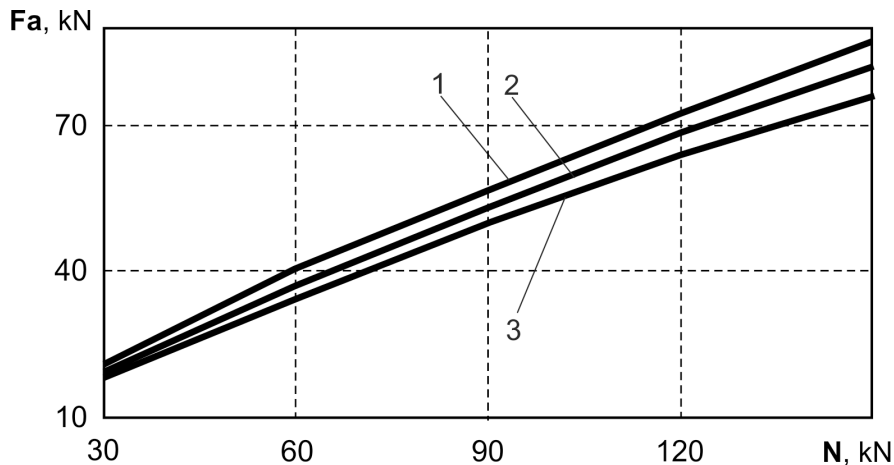


Fig. 4. The dependence of the adhesion force F_a on the magnitude of the normal wheel load on the rail N in the presence of solid particles in the contact area: 1 – quartz sand; 2 – iron scale; and 3 – magnetite

The results obtained were verified for the absence of rough errors using Student's t-test. The values of the confidence limits $\pm\Delta F_a$ for the magnitude of the adhesion force of the wheel with rails F_a (with a confidence figure $\alpha = 0.95$) and the corresponding values of the average standard deviations $F_a\sigma$ are listed in Table 2.

Table 2

Measurement errors of the magnitude of the value of adhesion force of the wheel to rail F_a

N, kN	Statistical characteristics, kN	Bulk material		
		Sand	Iron scale	Magnetite
1	2	3	4	5
30	$F_a\sigma$	2.15	1.69	1.37
	ΔF_a	0.84	0.66	0.54
1	2	3	4	5
60	$F_a\sigma$	3.33	2.85	2.74
	ΔF_a	1.30	1.12	1.07
90	$F_a\sigma$	5.48	4.41	3.26
	ΔF_a	2.15	1.73	1.28
120	$F_a\sigma$	6.94	3.03	2.32
	ΔF_a	2.72	1.18	0.91
150	$F_a\sigma$	12.74	9.19	6.67
	ΔF_a	4.50	3.60	2.61

From the obtained experimental results, it follows that iron scale and magnetite are slightly inferior to quartz sand by the criterion of the adhesion force of the wheels to rails, not more than 5% and 10%, respectively.

CONCLUSIONS

- The developed electromagnetic system used for improving the adhesion of the wheels to rails allows the supply of the magnetic abrasive material into the contact area between the wheels and rails with adjustable performance over a wide range. This allows the magnetic abrasive material to be supplied under the wheels of a locomotive in the initially defined mode.
- The presence of electromagnets to magnetize the surfaces of the wheel and rail in the system used for adhesion improvement allows the minimization of the loss of abrasive loose material when it is transported under the wheels of a locomotive.
- The presence of magnetic properties in iron scale and magnetite creates the prerequisites for a significant reduction in their consumption, compared with the use of silica sand. This is achieved because of the long-term magnetic retention of particles of these materials on the surface of the wheel. As a result, iron scale and magnetite can be fed to the contact area between the wheels and rails in smaller quantities compared with quartz sand.
- Reducing the consumption rate of iron scale and magnetite compared with quartz sand leads to a decrease in clogging of the ballast section of the railroad tracks with waste particles of these materials.
- Minimizing the consumption of abrasive loose material significantly reduces the contamination of the rail. In this case, the cleaning of the rail can be easily carried out by the magnetic extraction of the used abrasive loose material from the rail.
- The results of the study obtained allow us to conclude that the use of iron scale and magnetite is promising in order to improve the adhesion of wheels to rails. The proposed system for improving the adhesion of wheels to rails ensures the delivery of iron scale and magnetite to the working area and the long-term magnetic retention of particles of these materials on the surface of the wheels.

References

1. Olofsson, U. & Zhu, Y. & Abbasi, S. & Lewis, R., & Lewis, S. Tribology of the wheel-rail contact – aspects of wear, particle emission and adhesion. *Vehicle System Dynamics*. 2013. Vol. 51(7). P. 1091-1120. Special Issue: State of the art papers of the 23rd IAVSD Symposium.
2. Cann, P.M. The ‘leaves on the line’ – a study of leaf residue film formation and lubricity under laboratory test conditions. *Tribol. Lett.* 2006. Vol. 24. P. 151-158.
3. Li, Z. & Arias-Cuevas, O. & Lewis, R. & Gallardo-Hernandez, E.A. Rolling-sliding laboratory tests of friction modifiers in leaf contaminated wheel-rail contacts. *Tribol. Lett.* 2009. Vol. 33. P. 97-109.
4. Abbasi, S. & Olofsson, U. & Zhu, Y. & Sellgren, U. Pin-on-disc study of the effects of railway friction modifiers on airborne wear particles from wheel-rail contacts. *Tribology International*. 2013. Vol. 60. P. 136-139.
5. Baek, K.S. & Kyogoku, K. & Nakahara, T. An experimental investigation of transient traction characteristics in rolling-sliding wheel/rail contacts under dry-wet conditions. *Wear*. 2007. Vol. 263. P. 169-179.
6. Eadie, D.T. & Santoro, M & Kalousek, J. Railway noise and the effect of top of rail liquid friction modifiers: Changes in sound and vibration spectral distributions in curves. *Wear*. 2017. Vol. 258. P. 1148-1155.

7. Steenbergen, M. Rolling contact fatigue: Spalling versus transverse fracture of rails. 2017. *Wear*. Vol. 380. P. 96-105.
8. Kalousek, J. Keynote address: Light to heavy, snail to rocket. *Wear*. 2002. Vol. 253. P. 1-8.
9. Alarcón, G.I & Burgelman, N & Meza, J.M. & Toro, A. & Li, Z. Power dissipation modeling in wheel/rail contact: Effect of friction coefficient and profile quality. *Wear*. 2016. Vol. 366. P. 217-224.
10. Baek, K.S. & Kyogoku, K. & Nakahara, T. An experimental study of transient traction characteristics between rail and wheel under low slip and low speed conditions. *Wear*. 2008. Vol. 265. P. 1417-1424.
11. Arias-Cuevas, O & Li, Z. Field investigations into the performance of magnetic track brakes of an electrical multiple unit against slippery tracks. Part 2: Breaking force and side effects. *Proc. Inst. Mech. Eng. (Part F J. Rail Rapid Transit)* vol. 226). 2011. P. 1-23.
12. Arias-Cuevas, O. & Li, Z. & Lewis, R. Investigating the lubricity and electrical insulation caused by sanding in dry wheel-rail contacts. *Tribol. Lett.* 2010. Vol. 37. P. 623-635.
13. Olofsson, U. & Lyu, Y. Open System Tribology in the Wheel-Rail Contact-A Literature Review. *Applied Mechanics Reviews*. 2017. Vol. 69. P. 1-10. doi:10.1115/1.4038229.
14. Spiriyagin, M. & Wolfs, P. & Cole, C. & Spiriyagin, V. & Sun, Y. & McSweeney, T. *Design and simulation of heavy haul locomotives and trains*. Ground Vehicle Engineering Series. CRC Press. Taylor & Francis Group. USA. 2016.
15. Cao, X. & Huang, W.L. & He, C.G. & Peng, J.F. & Guo, J. & Wang, W.J. & Liu, Q.Y. & Zhu, M.H. The effect of alumina particle on improving adhesion and wear damage of wheel/rail under wet conditions. *Wear*. 2015. Vol. 348. P. 98-115. doi:10.1016/j.wear.2015.12.004.
16. Zhu, Y. & Chen, X. & Wang, W.J. & Yang, H. A study on iron oxides and surface roughness in dry and wet wheel-rail contacts. *Wear*. 2015. Vol. 328-329. P. 328-329. doi: 10.1016/j.wear.2015.02.025.
17. Осенин, Ю.И. & Соснов, И.И. Экспериментальное исследование сцепления колеса локомотива с рельсом при наличии в зоне контакта твердых частиц. *Вісник Східноукраїнського національного університету*. 2003. Т. 1. № 9. С. 41-45. [In Russian: Osenin, Y.I. & Sosnov, I.I. Experimental study of the adhesion of the locomotive wheel to the rail in the presence of solid particles in the contact zone. *Bulletin of Shidnoukrainskiy National University*. 2003. Vol. 1. No. 9. P. 41-45].
18. Соснов, И.И. Экспериментальное исследование изнашивания пар трения-качения с проскальзыванием при наличии твердых частиц в зоне контакта. *Вісник Східноукраїнського національного університету*. 2004. № 5. С. 135-140. [In Russian: Sosnov, I.I. Experimental study of the wear of friction-rolling pairs with slip in the presence of solid particles in the contact zone. *Bulletin of Shidnoukrainskiy National University*. 2004. No. 5. P. 135-140].
19. Козлов, А.А. Исследование намагниченности концов рельсов в изолирующих стыках разной конструкции. *Вестник ВНИИЖТ*. 2005. № 2. С. 36-40. [In Russian: Kozlov A.A. Investigation of the magnetization of the ends of the rails in the insulating joints of different designs. *Vestnik VNIIZhT*. 2005. No. 2. P. 36-40].
20. Антонов, А.С. & Козлов, А.А. & Козлов, А.С. Намагниченность рельсов. *Путь и путевое хозяйство*. 2008. № 2. С. 6-8. [In Russian: Antonov, A.S. & Kozlov, A.A. & Kozlov, A.S. Magnetization of rails. *Way and road economy*. 2008. No. 2. P. 6-8].
21. Смирный, М.Ф. & Бихдрикер, А.С. Определение оптимальных размеров головки записи устройства для взвешивания железнодорожных транспортных единиц. *Вісн. Східноукр. нац. ун-ту ім. В. Даля*. 2009. № 12. С. 119-125. [In Russian: Smirny, M.F. & Bihdriker, A.S. Determination of the optimum size of the head of the device for weighing railway transport units. *Bulletin of Shidnoukrainskiy National University named after V. Dal*. 2009. No. 12. P. 119-125].
22. Wang, W.J. & Zhang, H.F. & Liu, Q.Y. & Zhu, M. & Jin, X. Investigation on adhesion characteristic of wheel/rail under the magnetic field condition. *Proceedings of the Institution of Mechanical Engineers. Part J. Journal of Engineering Tribology*. 2015. Vol. 230. doi:10.1177/1350650115606480.

23. Осенін, Ю.І. & Соснов, І.І. & Осенін, Ю.Ю. Пристрій для поліпшення зчеплення колеса з рейкою. *Патент на корисну модель № 123244*. Україна. Опубл.: 26.02.2018. Бюл. № 4. [In Ukrainian: Osenin, Yu.I. & Sosnov, I.I. & Osenin, Yu.Yu. A device for improving the adhesion of the wheel with a rail. *Patent for Utility Model No. 123244*. Ukraine. Published: 02/26/2018. Bul. No. 4].
24. Старченко, В.Н. К вопросу о трении и сцеплении при взаимодействии колеса с рельсом. *Вісн. Східноукр. нац. ун-ту*. Луганськ. 2003. № 9. С. 129-135. [In Russian: Starchenko V.N. On the question of friction and adhesion in the interaction of a wheel with a rail. *Bulletin of Shidnoukrainskiy National University – Lugansk*. 2003. No. 9. P. 129-135].
25. Исаев, И.П. & Голубенко, А.Л. Совершенствование экспериментальных исследований сцепления колеса локомотива с рельсом. *Железные дороги мира*. 1983. № 10. С. 20-24. [In Russian: Isaev, I.P. & Golubenko, A.L. Improving experimental studies of the adhesion of a locomotive wheel with a rail. *Railways of the world*. 1983. No. 10. P. 20-24].

Received 25.07.2017; accepted in revised form 07.03.2019