Наведені результати експериментального дослідження впливу двошарового мащення, що формується з графітового порошку та базових молекул індустріальної оливи, на зносостійкість бічної поверхні головки залізничної рейки. Так, при збільшені концентрації графітового порошку в оливі від 0 до 3 % при навантаженні 363–646 N величина зношування зменшується на 42–29,7 % відповідно.

Методика досліджень передбачала моделювання процесу тертя кочення з проковзуванням за допомогою роликів на машині тертя СМЦ-2. Саме такий вид тертя має місце в трибосистемі гребінь колеса – бічна поверхня головки рейки в кривих ділянках колії. Також передбачалась подача оливи аерозольним способом. Варіювались два незалежних фактори: концентрація графітового порошку в індустріальній оливі И-12А та зовнішнє навантаження. Незмінними факторами залишались частота обертання роликів, що забезпечувало стабільне проковзування на рівні 20 %, температура оливи, час проведення кожного випробування.

Результати експерименту дозволили отримати рівняння регресії, яке описує закономірність зношування ролика пари тертя «ролик – ролик» в залежності від обраних факторів.

На завершальному етапі роботи був проведений розрахунок ресурсу рейки в кривій ділянці колії. Результати розрахунку ресурсу залізничної рейки за умов збільшення концентрації графітового порошку від 0 до 3 % при зовнішніх навантаженнях від 363 до 646 N показали приріст ресурсу рейки від 40 до 61 %. Розрахунок базувався на отриманих експериментальних даних, що характеризують процес тертя бічної поверхні головки рейки з гребенем колеса в кривій ділянці колії за умов двошарового мащення при різних навантаженнях. Двошарове мащення формувалось шляхом аерозольного нанесення оливи на поверхню тертя з різною концентрацією графіту.

Отримані дані дають можливість прогнозувати строк служби залізничних рейок в кривих за умов двошарового мащення

Ключові слова: графітовий порошок, двошарове мащення, колесо – рейка, трібологічна система, зносостійкість, аерозоль

ESTABLISHING A PATTERN IN THE INFLUENCE OF TWO-LAYER GREASING ON THE WEAR RESISTANCE OF RAILS

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1. Introduction

The practical experience of railroad operation demonstrates that one of the main problems in the interaction between rolling stock and a track is the interaction between a wheel and a rail. This is due to the high contact stresses that arise in a contact area and affect the condition of such a tribosystem. A particularly complicated and important issue is the interaction of a wheelset in a curved track section, as a wheel is (mostly) in contact with a rail at two different points.

That is, it forms the contact area on the rolling surface of a rail and on the side surface of a rail head – a two-point contact. A zone where the side surface of a rail touches the wheel flange is a place where the friction process of rolling with slippage is implemented. This process, due to the varying degree of the flange and side surface of rail wear, is accompanied by a change in the shape of pressure distribution. A contact area decreases, resulting in increased contact pressures [1]. Together, these processes lead to the emergence of a series of defects [2–4] and increase the wear intensity of rails in the curved track sections. It is a relevant task to resolve this issue as it affects the material and energy costs and, most importantly, traffic safety [5–9].

2. Literature review and problem statement

The main way to solve the task of increasing the durability of rails in the curved track sections is to apply a lubrication material onto the side surface of the rail. It should provide a decrease in wear intensity by reducing the contact pressure. This is possible under the condition of two-layer greasing.

Two layers are formed at two-layer greasing. The first one (lining) is formed from the alloying additives, which include the micro- or nanoparticles of metals, graphite, molybdenum disulfide, natural minerals, etc. It performs the function of distributing the external loads by filling the cavities in the surface micro irregularities. This contributes to decreasing actual pressures and extending the physical range of the second layer. The second one (a crystalline layer) is formed from surfactants (SAS) (an additive's molecules) or base molecules of a lubricating material, which perceive the external distributed load. This combination of layers significantly reduces the coefficient of friction by implementing the shear in the polycrystalline layer of SAS. Thus, the implementation of two-layer greasing is possible by using grease or oil, provided they contain a certain concentration of alloying additives.

The expediency of using lubricants with alloying additives in the tribosystems, in particular wheel-rail, was addressed in a series of studies [10–17]. Thus, work [10] investigated the impact of ten different types of lubricants on the coefficient of traction, resistance, and wear under conditions of «complete lubrication» and «lubricant fasting». However, the authors did not determine the impact of the concentration of certain alloying supplements on the durability of rail steel because they used different types of lubricants with their additives. Paper [11] described the results of the influence of the main characteristics of various lubricants used to lubricate a pair of friction «wheel-rail» on forces in the contacts between a wheel and a rail and on the rolling stock dynamics. However, the authors did not consider the dependence of wear resistance of the side surface of a rail head on the alloying additives in lubricants. In part, this issue was tackled in study [12]. The oil, which was fed to the friction pair «wheel-rail», caught the wear products from the interaction between a wheel and a rail, which formed a paste-like substance that contributed to a decrease in the coefficient of friction. However, the cited study did not establish the percentage of such wear products and their direct impact on the durability of a rail. The effect of the concentration of a disulfide molybdenum alloying additive to grease on the wear process of chrome-plated steel balls was considered in paper [13]. This paper implemented the rolling friction process, which does not correspond to the process of friction between a wheel flange and the side surface of a rail head,

that is the friction with slippage. Work [14] gave a better account of the impact exerted by the process of two-layer greasing on friction. The authors used, as an alloying additive for titanium lubrication that forms a substrate, nano-graphite containing particles of three different diameters (2 μm, 3.5 μm, and 6 μm). It was determined that the optimum concentration of three types of nano-graphite is 0.8 % by weight, 1.0 % by weight, and 1.2 % by weight. In addition, the optimum greasing by a titanium compound lubricant is greasing when the concentration of nano-graphite is 0.8 % by weight. However, the study was conducted at a four-ball friction machine, which did not match the processes implemented in the friction pair «the side surface of a rail-wheel flange». The implementation of two-layer greasing using oil with carbon nanoparticles as alloying additives is described in work [15]. The cited work established a decrease in wear rate by 11 %. The wear rate was determined at a four-ball friction machine, which implemented a spot contact of metal balls, but a given procedure does not make it possible to implement the process of rolling friction with slippage. The authors did not establish the wear rate dependences on the concentration of carbon nanoparticles. In [16], a rational concentration of carbon soot was found in an industrial oil, which is an alloying additive, which provided for minimal wear. However, the authors simulated the slip friction pair «steel – bronze».

The implementation of two-layer greasing by using an aerosol technique was considered in work [17]. The authors used, as oil with alloying additives, the commercially available Liqui Moly 10W40 oil with molybdenum disulfide. However, they focused on establishing the aerosol rail greasing parameters in order to ensure the stability of two-layer greasing on the side surface of a rail head. The Liqui Moly is commercially available; the concentration of the alloying additive was not known.

Thus, our analysis allows us to argue about the expediency of undertaking a study into the effect of graphite concentration in an industrial oil on the rail wear resistance. The two-layer greasing is performed by the aerosol application of oil with graphite.

3. The aim and objectives of the study

The aim of this study is to establish patterns in the impact of two-layer greasing on the wear resistance of railroad rails. This would make it possible to theoretically-experimentally substantiate the application of greasing in the curved track sections, taking into consideration the freight load, as well as to predict the resource of rails depending on freight load under conditions of two-layer greasing.

To accomplish the aim, the following tasks have been set:
– to determine a change in the wear of rail steel depending on the concentration of graphite powder and external load;
– to establish the resource of a rail depending on the concentration of graphite powder under various external loads.

4. Materials and methods to study the impact of two-layer greasing on the wear resistance of rails

4. 1. Materials and equipment used in the experiment

The study was conducted under laboratory conditions. To this end, a laboratory installation was designed, which enabled the simulation of tribological processes in the friction

pair «a wheel flange – a railroad rail». The installation is schematically shown in Fig. 1.
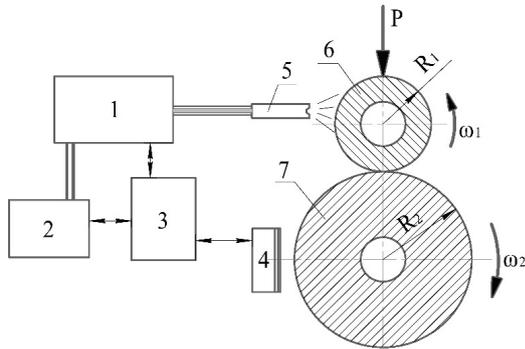

Fig. 1. Schematic of the installation for wear tests:
1 — oil and air feed unit; 2 — air compressor;
3 — electronic control unit; 4 — rotation sensor; 5 — injector;
6 — roller (rail steel); 7 — roller (wheel steel)

We have chosen the friction pair «roller – roller» as a physical model of the friction pair «a wheel flange – a railroad rail». This particular pair makes it possible to implement the process of rolling friction with slippage over a small area of contact. The rollers were made from the materials similar to those used to produce rails and wheel flanges.

The rollers were mounted on the friction machine SMC-2, which made it possible to adjust the rotation speed and create an external load. The aerosol application of the lubricating material into a friction pair was enabled by nozzle 5 to which, along a coaxial pipeline, air and oil were fed from feeder unit 1. The system was managed by electronic control unit 3, which, using compressor 2, maintained pressure in the system and, acquiring data from sensor 4, controlled the process of injecting a lubricating material.

We used, as a lubricant, the industrial oil, subgroup A, brand I-12, in line with GOST 20799-88, because it is the purest in terms of the presence of «additives». We applied graphite of grade C-0, namely a colloidal graphite preparation, TU 113-08-48-63-90, with the primary particle size of $1-2\,\mu m$. The concentration in the examined samples of oil was within $0-3\,\%$. This is due to the requirements for lubrication when implementing two-layer greasing by aerosol application, which were substantiated in works [18, 19].

The wear of samples was determined based on establishing the loss of their mass during tests, which lasted 1 hour. The samples were weighed at the analytical scales BLA-200 g-M with an accuracy of 0.0005 g.

4. 2. Procedure for determining the impact of two-layer greasing on the wear of rails

To implement the rolling friction with slippage at the installation shown in Fig. 1, the primary task was to maximally simulate the tribophysical processes occurring in the contact area between a flange and the side surface of a rail head. To this end, we calculated the contact's contour area taking into consideration the results reported in [1, 20–23]; it was $120\cdot10^{-6}\,m^2$. Given the contour area of the contact between a flange and the side surface of a rail head, as well as the roughness of their surfaces, and load, we calculated the actual contact area. Using the actual contact area and the forces operating from a wheel flange on the side surface of a rail head [20–23], we determined the specific pressure

formed in the contact area. Based on the results obtained, we recalculated the loads in order to conduct an experiment in line with the following expression:

$$P = \frac{\pi \cdot H_{rol} \cdot \left(\dfrac{P_{bok}}{S_{kon}}\right)^2 \cdot \left(\dfrac{1-\mu_1^2}{E_1} + \dfrac{1-\mu_2^2}{E_2}\right)}{\dfrac{1}{R_1} + \dfrac{1}{R_2}}, \tag{1}$$

where H_{rol} is the examined rollers' width, m; P_{bok} is the lateral load from a wheelset on a rail, N; S_{kon} is the actual contact area «wheel-rail», m^2; μ_1 is the Poisson rail steel coefficient; μ_2 is the Poisson wheel steel coefficient; E_1 is the elasticity module of rail steel; E_2 is the elasticity module of wheel steel; R_1 is the roller radius (rail steel); R_2 id the roller radius (wheel steel).

Thus, the experiment conditions are as follows:
– a roller radius, $R_1 – 0.0125$ m, $R_2 – 0.04$ m;
– roller width is 0.01 m;
– the rotation frequency of rollers, $n_1 = 240$ rpm, $n_2 = 300$ rpm (slippage is, accordingly, 20 %);
– a spindle rotation frequency is $n = 300$ rpm;
– a stabilized temperature of the tank with oil is $t = 20\pm5\,°C$;
– the time of one test is $t = 1$ hour.

Thus, we defined the conditions of the experiment and the range of fluctuations of independent factors, given in Table 1.

Table 1

Independent factors and experiment conditions

Independent factors		Experiment conditions			
P, (N)	C, (%)	ω_1, rpm	ω_2, rpm	R_1, m	R_2, m
363	0				
495	1.5	240	300	0.0125	0.04
646	3				

In order to determine the minimum required repeatability of experiments, we preliminary performed ten measurements of the wear of roller R_1 in the pair «roller – roller». The measurements involved the industrial oil I-12A without the addition of graphite powder. The oil temperature during the measurements was 20 °C; the external load on the friction pair – 530 N. The results of preliminary tests are given in Table 2.

Table 2

The results of preliminary tests to determine the minimum required number of experiments

Experiment No.	1	2	3	4	5
Roller wear, mg	35.329	36.375	36.06	35.518	36.504
Experiment No.	6	7	8	9	10
Roller wear, mg	35.928	36.839	36.676	36.423	36.197

Based on the theory of experiment planning and the methods of statistical treatment of mechanical measurement results [24, 25], we calculated the required minimum number of experiments: the results are given in Table 3.

The minimum required repeatability of experiments was determined from the following dependence:

$$n_{min} \geq \frac{\sigma^2 \cdot t_{cr}^2}{\Delta^2 \cdot m^2}, \tag{2}$$

where σ is the arithmetic mean deviation of measurements; t_{cr} is the tabular value of Student coefficient at the predefined reliability of measurement results $P=0.9$ and the number of experiments $n=10$, $t_{cr}=1.81$ [24]; Δ is the permissible relative error of measurement ($\Delta=0.02$ [25]); m is the arithmetic mean of measurement results.

Table 3

Results of calculating the minimum number of experiments at the friction machine SMC-2

Measured indicator	The standard deviation of measurements, σ	The arithmetic mean of the measurement results m	The minimum required repeatability of experiments, n_{min}
Roller wear	0.235861	36.1849	1.475359

Thus, the minimum repeatability of experiments, $n_{min}=2$.

The program of experimental studies implied the implementation of one 2-factor experiment in which a response function was the roller wear in the pair «roller – roller» (Table 4).

In order to obtain dependences in the form of regression equations, the orthogonal plan of the experiment was selected, which made it possible, at a minimum number of experiments, to determine the coefficients of the equations at the assigned confidence probability.

Table 4

The program of experimental studies of roller wear R_1 in the friction pair «roller — roller» at the friction machine SMC-2

Experiment No.	Response function	Oil brand	Additive, %	External load, N
1	Roller wear R_1, mg	I-12A	The concentration of graphite powder (0–3 %) in oil	363–646 N

According to the recommendations from [25, 26], the levels of factor variation (Table 5) were selected, and the orthogonal plan for the two-factor experiment was compiled, Table 6.

Table 5

Levels of factor variation

Level	Code	External load P, N; X_1	The concentration of graphite powder C, %; X_2
Lower level	−1	363	0
Zero level	0	495	1.5
Upper level	+1	646	3

Table 6

Orthogonal plan for a two-factor experiment

No. of entry	Encoded values		Natural values	
	X_1	X_2	External load P, N	The concentration of graphite powder C, %
1	0	1	495	3
2	1	0	646	1.5
3	−1	−1	363	0
4	−1	0	363	1.5
5	1	1	646	3
6	0	−1	495	0
7	1	−1	646	0
8	−1	1	363	3
9	0	0	495	1.5

Thus, to determine the impact of the concentration of graphite powder and external load on roller wear R_1 in the pair «roller – roller», we carried out 1 two-factor experiment. This experiment involved 9 experiments with each one repeated twice.

5. Results of studying the impact of two-layer greasing on the wear of rails

5. 1. The results of a change in the wear of rail steel depending on the concentration of graphite powder and external load

The results of the experimental study at the SMC-2 friction machine are given in Table 7.

Table 7

Results of an experimental study on determining the roller wear R_1 in the friction pair «roller — roller» depending on the concentration of graphite powder in oil I-12A and external load

No. of entry	Roller wear R_1, mg		
	I_1	I_2	I_{ave}
1	19.108	18.676	18.892
2	55.558	55.189	55.3735
3	10.046	10.261	10.1535
4	6.473	6.890	6.6815
5	50.812	51.022	50.917
6	28.041	28.855	28.448
7	72.568	72.267	72.4175
8	5.910	5.949	5.9295
9	20.650	21.369	21.0095

Based on the results of our study, a regression equation was derived, describing the wear pattern of roller R_1 in the friction pair «roller – roller» depending on the selected factors when using oil I-12A (4). In order to improve the adequacy of the obtained model, we refused the polynomial notation of the equation and, using the «STATISTICA» software suite, chose an equation in the general form:

$$I = a \cdot P^2 - b \cdot P - \frac{c}{C+1} + \frac{d \cdot P}{C+1} + e, \tag{3}$$

where a, b, c, d, e are the equation coefficients.

The equation coefficients were also calculated in the software suite «STATISTICA», and the resulting regression equation takes the following form:

$$I = 0.00054 \cdot P^2 - 0.3775 \cdot P -$$
$$- \frac{35.4988}{C+1} + \frac{0.1094 \cdot P}{C+1} + 72.6439, \tag{4}$$

where I is the weight roller wear, mg; P is the load on a roller, N; C is the concentration of graphite powder in oil, %.

We checked the reproducibility of experiments according to the Cochran's criterion [24, 25]; the model adequacy was validated using a Fisher criterion [24].

The results of testing for reproducibility and adequacy are given in the following equations:

– determining roller wear R_1:

$$G_C = 0.323960 \le 0.6385, \quad F_F = 5.271159975 \le 6.1631.$$

The derived regression equation is adequate for the obtained experimental results; therefore, it is possible to apply them to analyze studies.

The graphic representation of the results from testing the effect of the concentration of graphite powder on a change in the wear R_1 in the friction pair «roller–roller» under an external loaded (363–646 N) at the SMC-2 machine is shown in Fig. 2 and Fig. 3.
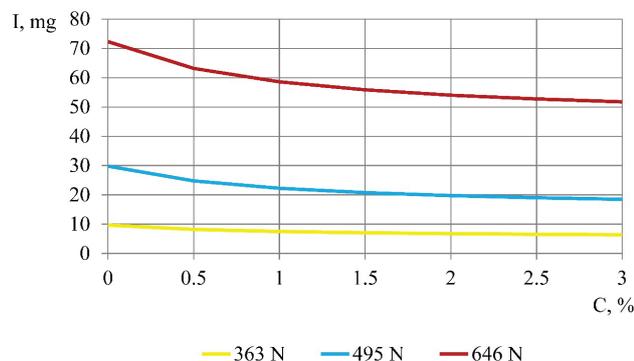

Fig. 2. Change in the amount of roller wear R_1 depending on the concentration of graphite powder in the industrial oil I-12A under different external loads
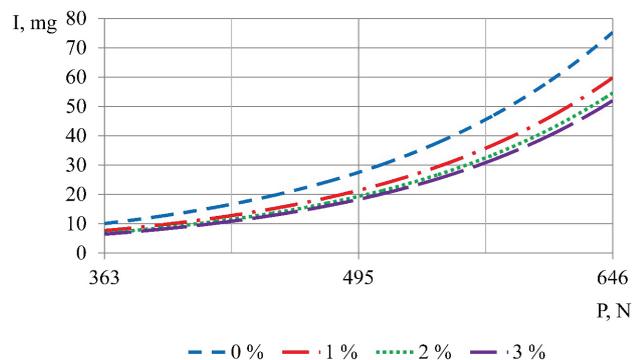

Fig. 3. Change in the amount of roller wear R_1 depending on the external load at different concentrations of graphite powder in oil I-12A

Based on the study results (Fig. 2, 3), we established the dependence of change in the roller wear R_1 on the concentration of graphite powder in the oil and on an external load. It was discovered that increasing the concentration from 0 to 3 % under external loads from 363 N to 646 N decreases the roller wear.

5. 2. Calculation of the rail resource depending on the concentration of graphite powder under different external loads

The derived experimental data on the influence of two-layer greasing at different concentrations of graphite powder on roller wear under different loads allow us to recalculate the resource of rails under these conditions. The rail resource should be determined in tons of cargo received.

Thus, the resource of rails is determined as follows:

$$T = \frac{S_{rol} \cdot h_{lim} \cdot \rho_{st}}{I_{IC}} \cdot \frac{m_{vag}}{n_{par}}, \tag{5}$$

where S_{rol} is the roller working surface area, m²; h_{lim} is the threshold of a rail lateral wear, m; ρ_{st} is the density of rail

steel, kg/m³; m_{vog} is the car mass, t; n_{par} is the number of wheelsets per a single car, units; I_{IC} is the weight roller wear over one rotation, mg/rev.

Unknown in expression (5) is the weight roller wear over a single rotation, which is determined from:

$$I_{IC} = \frac{I}{\omega \cdot t}, \tag{6}$$

where ω is the frequency of roller rotations, rpm; t is the duration of one experiment, min.; I is the weight roller wear, mg.

Substituting expression (6) into (5), we obtain:

$$T = \frac{S_{rol} \cdot h_{lim} \cdot \rho_{st} \cdot \omega \cdot t}{I} \cdot \frac{m_{vag}}{n_{par}}. \tag{7}$$

The graphic interpretation of the calculation of a rail resource is shown in Fig. 4.
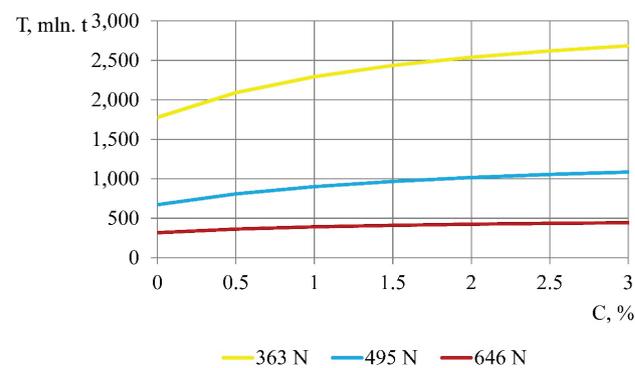

Fig. 4. Resource of a rail depending on the concentration of graphite powder in the industrial oil I-12A under different external loads

The results of calculating the resource of a rail (Fig. 4) under conditions of an increase in the concentration of graphite powder from 0 to 3 % at external loads from 363 N to 646 N showed the increase in the rail resource from 40 % to 61 %.

6. Discussion of results of studying the influence of the concentration of graphite powder on rail wear resistance

A decrease in the wear of the friction pair «wheel-rail» at the concentration of graphite powder in the oil from 0 to 3 % is associated with the influence of two-layer greasing on the characteristics of friction (Fig. 2). First of all, this is due to the filling of the microscopic irregularities at the contact surface with a layer of solid antifriction additive, which is graphite. This process contributes to the increase in the actual contact area almost to the size of the contour, which leads to the uniform distribution of the external load and, consequently, the reduction of the specific pressure in the contact area «a wheel flange – the side surface of a rail head». It also positively influences the formation of a boundary layer from the molecules (in this case) of the base oil I-12A. It is known that boundary layers are formed only on the actual area of contact, that is, on the deformed (or worn) tops of microscopic protrusions of friction surfaces that are constantly formed due to the elastic-plastic contact, shear, or the cutting of micro protrusions. That is, increasing the actual contact area to the

magnitude of a contour one makes it possible to expand the range of formation and action of the polymolecular boundary layer, as well as increase bearing ability due to the denser arrangement of molecules. This combination of the two layers leads to a decrease in the friction forces in the contact area due to the implementation of the «light» shear in a polymolecular boundary layer. It thus increases the wear resistance of the side surface of a rail head when interacting with the flange of the wheel under conditions of two-layer greasing.

The results of this work confirm the conclusions from earlier scientific studies [3, 4, 15–18, 28–30] on the positive use of lubricants with alloying additives in the friction pair «wheel-rail». However, it should be noted that the authors of papers [10, 11, 13, 14] used plastic lubricants, and works [14, 15, 28, 29] applied, as additives to oils, a variety of forms of carbon; the application of lubricants in the cited works did not involve an aerosol technique. It should also be noted that the cost of obtaining alloying additives based on different forms of carbon is higher than graphite powder.

The limitation of this study is that it is possible to receive adequate results under the following conditions:

– the presence of the industrial oil, subgroup A, brand I-12A, in line with GOST 20799-88;

– the concentration of graphite powder, grade C-0, in line with TU 113-08-48-63-90 with the primary particle size of 1–2 μm in the oil – 0–3 %;

– an external load within 363–646 N;

– an aligned friction pair, made from rail steel of grade M-76 with the same strength.

No doubt operating conditions will have an impact on the stability of results. This is due to the fact that the same curve section is used by different rolling stock at different speeds and equipped with different wheels, which can be new, worn, or restored, as well they have different sizes, durability, and profile, which would directly affect the speed of defect evolution and the actual contact area, and, consequently, the durability and resource of the rail.

As regards the shortcomings of this work, one should note that we did not experimentally reveal the rational concentration of graphite powder in oil, not only in terms of wear but also the viscous-temperature characteristics of the oil, taking into consideration its aerosol application. Investigating these unresolved issues is a further scientific task.

7. Conclusions

1. It has been determined that the formation of a special anti-frictional coating on the working surface of a rail head by adding graphite powder to the industrial oil contributes to increased durability of the rail steel. Thus, increasing the concentration of graphite powder in the oil from 0 to 3 % at a load of 363 N decreases the amount of wear by 42 %. Under a load of 495 N the amount of wear decreases by 33.6 %, and at 646 N – by 29.7 %. The minimum wear, over the entire range of external loads, is observed at the value of the concentration of graphite powder of 3 %.

2. We have determined the rail resource depending on the concentration of graphite powder in the industrial oil under different loads. The calculation results showed that increasing the concentration of graphite powder in the oil from 0 to 3 % under a load of 363 N increases the rail resource by 1.51 times. Under a load of 495 N, the rail resource increases by 1.61 times; at 646 N – by 1.4 times.

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