Letters on Materials 15 (4), 2025 pp. 277-283 www.lettersonmaterials.com

Received 4 August 2025; Accepted 7 October 2025
https://doi.org/10.48612/letters/2025-4-277-283
https://elibrary.ru/zomuov

On the possibility of minimizing wear of the "wheel-rail" system using ultrafine mineral powders in combination with electric spark hardening

A. V. Skazochkin[†1,2], G. G. Bondarenko[3], S. V. Kislov[4], A. S. Useinov[5]

[†]avskaz@rambler.ru

[1]LLC "Kryokon", Kaluga 248010, Russia
[2]Research Institute of Advanced Materials and Technologies (RIAMT), Moscow 105187, Russia
[3]National Research University Higher School of Economics, Moscow 101000, Russia
[4]LLC "Research&Production Center "Mico-Tech", Kaluga 248010, Russia
[5]Vereshagin Institute for High Pressure Physics Russian Academy of Sciences, Moscow, Troitsk 108840, Russia

Abstract: The article presents the results of comparative studies of wear resistance of railway wheel samples with surface modification by ultrafine mineral powders and without modification. The tested samples are made of standard railway wheels made of CT2sp steel (ordinary quality carbon steel — an analogue of Q215 steel (China), A192 steel (USA), and RSt34–2 steel (Germany)), and the support rollers are made of E78HF rail steel (E76HF, Russia). The outer cylindrical surfaces are modified with ultrafine mineral particles (quartz, serpentine, tungsten carbide) using mineral coating technology. To introduce particles of mineral mixtures into the metal surface, the surface microtopography shape and subsequent ultrasonic surface treatment were used; the main tribological parameters of the sample surface before and after modification were determined. The study of wear resistance of railway wheel samples with a modified layer and samples without treatment after $6 \cdot 10^4$ test cycles showed that samples with mineral treatment increase the wear resistance of samples by 2.4 times compared to untreated samples. The tests also showed that the wheel rollers treated with minerals do not increase the wear of the counter rollers made of E78HF rail steel, which can help minimize the wear of the wheel-rail tribosystem and can be used for transport operating in conditions of abrasive dust, high humidity, and other aggressive environments.

Keywords: mineral coating, ultrafine mineral powders, surface modification, rail steel, railway wheel, wear resistance, hardness measurements, 3D optical images of the surface

Acknowledgments: *The authors are grateful to the vice-president of the German Society for Tribology, Dr. Mathias Woydt (Germany), for the preliminary review of the manuscript, valuable comments and advice.*

1. Introduction

The global railroad network encompasses, according to the International Union of Railways, 915473 tracked kilometres. In a globalized world, where most freights are shipped by marine vessels, and in order to reduce carbon emissions, railroad represent an upcoming and cost-effective alternative, as highlighted by projects like the Trans-Siberian Railway or the Silk Road. An increase in transportation volume is traditionally achieved by changing logistic streams and increasing the speed of trains, which leads to an increase in the wear rate of components and elements of the rolling stock and, accordingly, increases the costs associated with replacing worn parts and mechanisms.

Friction and accompanying friction processes of various natures, the intensity of which increases when trains pass turns, especially for small radius, cause additional wear of wheels and rails, increase energy consumption, and can disrupt the geometry of the rails [1]. For the Russian Federation, this factor is quite significant since the length of curved sections of the railway network (the origin of which is caused by the season's terrain, hydrography, etc.) is approximately 1/4 of the total length [2].

Traditionally, when analyzing the problem of friction in the "wheel-rail" contact, two main groups of the most influential factors are distinguished: dynamic and tribological [3–4]. The former depends mainly on the design of the rolling stock and its condition [5], and the latter on the wear resistance of the friction surface, the profile of the pair, the value of the friction coefficient of the wheel-rail pair and its stability depending on various external factors, such as temperature, rain, the presence of abrasives in the contact patch, climatic conditions, load, and speed [6].

The "wheel-rail" tribo-system is an unsealed tribo-system operating under difficult operating conditions when exposed to adverse environmental factors. A universal way to improve the interaction of the wheel-rail pair and, at the same time, stabilize some interaction parameters is to apply a lubricant to the track (top of rail) and the inner surface of the rails (flange lubrication) [7]. At the same time, many studies have demonstrated (for example, [8 – 9]) that in the "wheel-rail" contact, the most influential are three main types of wear: abrasive, which provides 36 – 58% of total wear; adhesive (23 – 45% general wear) and surface fatigue (14 –15% of total wear), depending on various factors.

It is well known that with abrasive wear, abrasion of metal particles of the wheel flange and the side face of the rail head occurs. With adhesive wear, destruction of the material of the wheel flange and rail occurs due to the adhesion (displacement) of the rubbing surfaces, accompanied by the scuffing and wear of a less hard material [8 – 9]. Fatigue wear is caused by contact stresses on micro-protrusions with a large axial load, which leads to the appearance of cracks, metal spalling (pitting) and peeling. In total, depending on various conditions, these three types of wear account for at least 2/3 of the total wear of the "wheel-rail" contact pair [8 – 9].

Traditional directions for reducing the wear of wheel-rail pairs include reducing the contact interaction of the wheel flange with the rail due to lubrication and changing the tribological properties of the wheel material [10]. In addition to contact lubrication, several well-known metallurgical technologies are currently used to improve the wear resistance of the flanges of rolling stock wheel sets: plasma technology, laser technology, and electric contact technology.

At the enterprises of Russian railways, plasma technology used to strengthen the metal of wheel flanges is quite common — as of the end of 2023, there were approximately 90 installations using this technology. Although plasma technologies have a wide range of applications, in this case the technology is used to harden the metal surface of a wheel in a chemically active and high-temperature gas stream (usually using methane, propane, or butane) and subsequent cooling [11]. As a result, the wheel metal hardens with the formation of martensite structures on the surface, accordingly, the hardness and wear resistance of the wheel surface increase, but the ductility decreases. However, if carried out periodically, plasma hardening can lead to the accumulation of defects, which, under conditions of regular deformation, can lead to destruction of the part [11].

Laser hardening is based on local heating of a surface area under the influence of laser radiation and subsequent cooling of this surface area at high speed as a result of heat removal into the bulk volume of the metal [12]. A high cooling rate leads to the formation of highly dispersed structures after cooling, including highly dispersed martensite [12,13]. However, the use of laser hardening in railway conditions requires highly qualified service personnel and special climatic, production (formation of absorbent coatings), and sanitary conditions on production premises. In addition, due to the relatively high cost, the use of laser technological complexes is not always economically justified. This is partly why laser technology is not widespread under railway conditions [12].

A promising technology that can improve the mechanical properties of the surface of parts used in railways is localized electrical spark hardening. As a result of the use of this technology, the surface layer of the wheel metal is modified. The transformation of the metal structure is carried out by the process of thermal cycling with hardening of the metal and subsequent tempering in the temperature range, which simultaneously provides the required strength and ductility [14 –15]. The disadvantages of this technology are the relatively low achievable hardness and the danger of surface micro-cracks in the event of sudden cooling. Small microcracks under contact loading conditions are unacceptable, as they spread and can contribute to the occurrence of further damage.

In practice, reducing the wear rate of wheel flanges and the rails themselves is also achieved by increasing the hardness of the surface layer via special alloying (formation of carbides), surface plastic deformation, heat treatment (formation of martensite and carbide particles), and chemical-thermal treatment [16]. To improve the crack resistance of rails, surface treatments (grinding and milling) are also carried out to eliminate discontinuities, scratches, and corrosion spots and remove unfavorable residual stresses [16].

Another technology that can increase the service life of wheel flanges under conditions of abrasive, adhesive, and fatigue wear is the so-called mineral coating technology [17–19]. This technology uses both electrical spark hardening in the technological cycle and ultrafine powders (0.5 – 5.0 μm in size) of minerals of natural origin or other substances to form a modified surface layer 3 – 30 μm thick by plastic deformation via ultrasonic and mechanical influences that activate the entry of ultrafine particles of minerals into the volume of metal [20 – 22]. As a result, a complex and durable surface modification is formed, which reduces friction, increases wear resistance, and increases anti-seize ability [17–19]. The basic technology serves as a basis for obtaining the necessary characteristics of the surface layers.

The purpose of this work was to perform a comparative study of the wear resistance of samples made of wheels made from Wheel Steel 2 (CT2sp) with a surface layer created using mineral coating technology and of samples of wheels made of CT2sp without coating under conditions simulating wear of the "wheel-rail" tribosystem.

2. Materials and experimental methods

Wear resistance tests were carried out on samples (rollers) made from the rim of a standard railway wheel made of wheel steel CT2sp (carbon steel according to GOST 10791-2011 — analogue to steel grade Q215 (China), A192 (USA), and European steel grade E195 (formerly RSt34-2 (1.0034)).

On the end surface of the studied samples, layers modified with ultra-dispersed mineral particles from a mixture of minerals were created using the technology of NPO "Geoenergetika" [17– 21]. The basic method of modifying a metal surface using mineral coating technology in combination with localized spark hardening consists of four steps [17]: surface texturing; the introduction of ultrafine mineral particles into the surface layer using ultrasonic indenters; spark hardening of the surface; and the use of ball and roller burnishing to smooth and compact the surface. The powders used were a mixture based on quartz, serpentine group minerals [17] and tungsten carbide, tested in [20] and subsequently used to increase the service life of the rail frog [19]. A total of 4 samples alloyed with minerals and 4 samples without coating were tested.

The counterbody samples were cut from a rail (hardened rail of category DT350 made of E78HF (E76HF, Russia) steel according to GOST R 51685-2022). The counterbody alloying with minerals was not carried out. It should be noted that E78HF steel has a fairly high carbon content, and vanadium is used as a microalloying element.

Wheel samples in the form of cylindrical rollers with a diameter of 40 mm and a thickness of 10 mm were machined out at a depth of 27 mm from the rolling surface, corresponding to the middle of the working layer of the metal of the wheel rim. Rail counter rollers with a diameter of 40 mm and a thickness of 6 mm were machined out directly from the rail head near the rolling surface.

The wear resistance test was carried out on an MI-1 friction machine of the AMSLER-type (twin disk) with an electrical drive, which was designed to study the mechanisms of friction and wear of metals and alloys under slip-rolling. The test mode involved rolling a wheel roller on a rail with a longitudinal slip of 10% at a constant contact load of 75 kgf and a Hertzian contact pressure of $P_{0\,mean} = 752$ MPa or $P_{0\,max}$ of 958 MPa (corresponding to the pressure on the contact area (spot) of the run-in profiles of the wheel and rail in operation with an axial load of 23.5 tons per axle) [25]. The rotation speed of the wheel roller was 195 rpm, the rotation speed of the rail roller was 217 rpm. Considering that the aim of the research was a comparative assessment of the wear resistance of wheel steels, the surface temperature of the rollers was not controlled; the experiment was conducted at room temperature.

The wheel roller was mounted on the upper shaft of the machine, and the rail counter roller was mounted on the lower (driving) shaft, after which a contact load of 75 kgf was applied. Before testing the rollers, they were run-in to eliminate possible deviations from the alignment of the rollers and to form a uniform and complete contact patch. After the rollers had been run-in, they were weighted prior to the test. To intensify the wear processes, no lubricant was supplied to the contact zone. The wear decrease during the tests was characterized by the mechanism of abrasion. Every $2\cdot10^4$ revolutions of the wheel roller, the friction machine was stopped, and the rollers were weighed. The testing of each set of samples was completed after $6\cdot10^4$ revolutions (three periods of $2\cdot10^4$ revolutions each), and the final weight wear of the wheel and rail rollers was recorded. Weighing the samples to determine wear was carried out on a scale with an accuracy of 0.001 g. During the tests, the number of roller revolutions was recorded using the mechanical counter, and the stability of the application of a normal load on the samples (75 kgf) was also monitored. A test duration of $6\cdot10^4$ revolutions is necessary and sufficient for a comparative assessment of the wear resistance of samples with and without a mineral doping technology in combination with localized electro-spark hardening. The precision of the mass losses using this method is not larger than 10%. The arithmetic average mass losses (wear) values for four samples of each set of rollers was taken as the test result.

Optical three-dimensional images of the surface topography and measurements of the surface roughness along the surface profile were obtained by the optical profilometry method on a 3D optical profilometer-confocal microscope S neox, manufactured by Sensofar (Spain). The parameters of the relief and roughness were used to determine the particle sizes of the mixtures during surface modification.

Hardness measurements on the Vickers scale were carried out using a NanoScan-HV microhardness tester (Advanced Scientific Devices, LLC, Russia) according to the recommendations of the GOST R ISO 6507-1-2007 standard. Measurement procedure parameters: indenter — Vickers tetrahedral pyramid; loads — 0.1, 0.2, 0.5, 1, 2, and 5 kg. Hardness measurements were used to roughly estimate the depth of modification and predict wear resistance.

Based on the results obtained, a quantitative comparative assessment of the wear resistance of wheel rollers with and without mineral coating was performed, and the following characteristics of the wear process were determined:

– wear rate (specific wear) of the wheel/rail sample — the difference in the mass of the wheel/rail sample between adjacent test periods, related to the number of revolutions of the machine's working shaft for one test period of $2\cdot10^4$ cycles;

– cumulative wear of the wheel/rail sample — the sum of the wear of the wheel/rail sample for all test periods of $6\cdot10^4$ cycles;

– the average wear resistance of the wheel/rail rollers of each type determined as the reciprocal of the average wear rate;

– the total wear of a friction pair determined as the sum of the average wear values of the wheel and rail rollers of each group.

3. Results and discussion

The essence of mineral coating technology is to create a modified surface layer by plastically deforming it using ultrasonic and mechanical effects that activate the entry of ultrafine mineral particles into the metal volume [26]. One of the technological methods for placing a particle into the metal volume is to use surface roughness to position the particles in depressions and irregularities that form the surface microrelief and then close the irregularities using ultrasonic treatment and rolling. Having determined the roughness parameters, it is possible to determine the average size of the particles that need to fill the depressions. Using the optical profilometry method on the S neox (Sensofar) device, the surface roughness was measured along the surface profile, and optical three-dimensional images of the surface topography were obtained at two magnifications: ×10 (1754×1320 μm) and ×50 (351×264 μm). Table 1 shows the roughness of the surface topography without coating.

Figure 1 shows optical three-dimensional images of the surface topography without coating.

Based on the size of the depressions, it is obvious that a particle no larger than 5 μm can be placed on the conventional

Table 1. Roughness of the surface topography without coating (R_a is the arithmetic mean deviation of the profile from the mean line, measured at a certain base length; R_q is the root-mean-square roughness).

Sample	Roughness, R_a (μm)	Roughness, R_q (μm)
No.3 ×10	1.71	2.06
No.3 ×50	1.5	1.72

"bottom" of the groove (highlighted in red, Fig. 1), provided that the peaks are further closed by the indenter. The mixtures used in the experiment had particle sizes of D_{90} = 1.6 μm after several types of grinding (electron microscopy, dispersion analysis). Of course, it was possible to use particles of a smaller diameter, but the cost of such grinding increases exponentially.

The result of measuring the surface roughness after creating a modified layer is presented in Table 2, and a three-dimensional image of the surface topography after modification is shown in Fig. 2.

The data in Table 2 and Fig. 2 show an improvement in the roughness parameters, which manifested itself in a significant decrease in the R_q parameter by more than 2.5 times (R_q is more sensitive to the presence of peaks and valleys on the surface and is used to evaluate precision surfaces), as well as in the absence of surface waviness. Sharp peaks in Fig. 2 are associated with the consequence of electro spark alloying of the surface after the ultrasonic treatment procedure and, if necessary, can be easily removed using knurling, which was not used in this case, since wear tests were subsequently carried out.

Hardness measurements on the Vickers scale were carried out using a NanoScan-HV microhardness tester using a Vickers-type tetrahedral pyramid. When carrying out hardness measurements, it is necessary to take into account that the surface after modification is quite non-uniform due to the fact that the process operations of mineral coating technology lead to the formation of both a smooth surface (about 90%) and chaotically located microcavities (about 10%) over the entire working surface of the samples ([17], Fig. 1 or [27], Figs. 6 and 7).

Considering that it is the smooth areas of the modified surface that play a dominant role in friction processes, and it is the parameters of the smooth areas of the surface that determine the properties of the surface during friction and wear [17, 27], indentation by the Vickers method was carried out precisely in the smooth areas of the modified surface (similar to work [27]). The expected thickness of the modified layer, based on the technological parameters during its creation, the depth of the surface relief grooves, and previously conducted experiments [17–18], should be no less than 5 μm but no more than 10 μm.

Hardness measurements of E78HF steel samples were taken at one load (0.1 kgf) in the middle between the modified surface centre and the sample edges. Each measurement was taken 3 times; the standard deviation is presented as an error. The results of hardness measurements are presented below in Table 3.

Considering that the dependence of the measured microhardness on the load value reaches a flat surface, equal to approximately one hardness value, at a load of more than 1 kg, it is likely that at such a load the Vickers pyramid "pierces" the modified, hardened layer, going beyond its limits. Based on the indentation depth, knowing the dimensions of the indenter and photographs of the prints of the microhardness determination procedure see Fig. 3, it can be approximately determined that the depth of the modified layer is no more than 6 – 8 μm.

The results of a quantitative comparative assessment of the wear process parameters and wear resistance of wheel rollers with and without mineral doping are shown in Table 4.

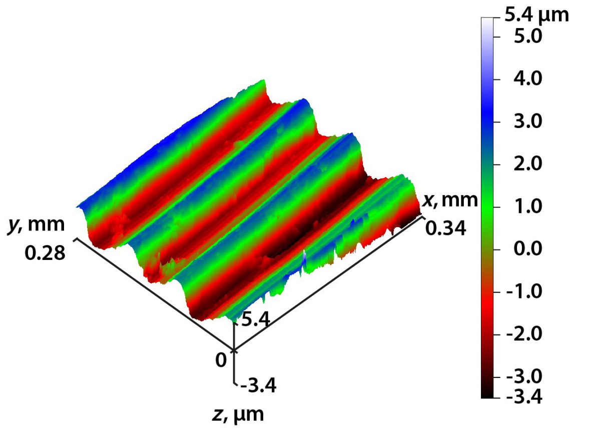

Fig. 1. (Color online) Three-dimensional image of the surface topography of an uncoated sample (magnification ×50).

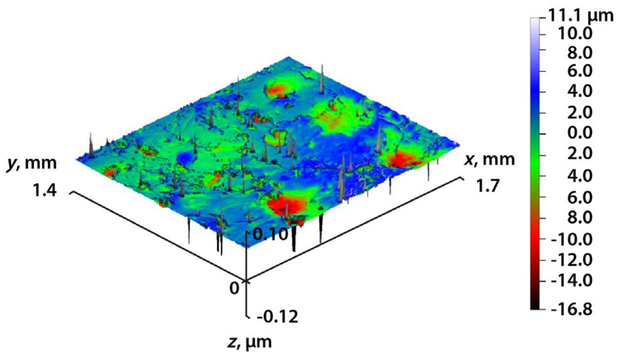

Fig. 2. (Color online) Three-dimensional image of the surface topography of the sample after modification (magnification ×10).

Table 2. Roughness of the surface topography with a coating (R_a is the arithmetic mean deviation of the profile from the mean line, measured at a certain base length; R_q is the root-mean-square roughness).

Sample	Roughness, R_a (μm)	Roughness, R_q (μm)
No.3 ×10	1.74	2.08
No.3 ×50	0.55	0.61

Table 3. Results of microhardness measurements of coated and uncoated samples made of CT2sp steel and samples made of E78HF rail steel.

Sample	Load, kg	Hardness, HV			
		1	2	3	Average
Steel CT2sp without coating	0.1	452	437	384	424 ± 36
	0.2	381	340	357	359 ± 21
	0.5	285	301	345	310 ± 31
	1	287	269	281	279 ± 9
	2	242	242	239	241.0 ± 1.7
	5	233	250	238	240 ± 9
Steel CT2sp with mineral coating	0.1	738	1001	572	770 ± 220
	0.2	360	409	776	520 ± 230
	0.5	298	289	508	370 ± 120
	1	271	375	305	317 ± 53
	2	288	281	289	286 ± 4
	5	258	238	235	244 ± 13
Steel E78HF	0.1	745	730	750	742 ± 12

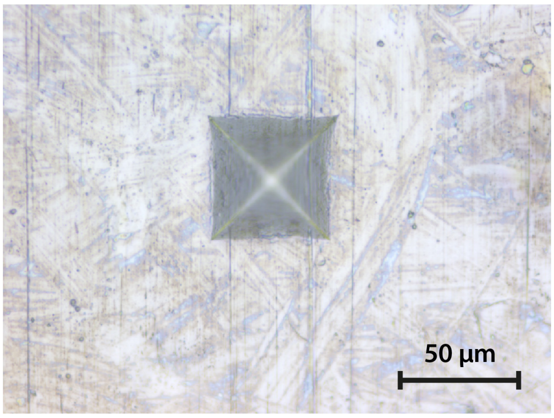

Fig. 3. Photograph of a Vickers indentation when determining the microhardness of a sample of CT2sp steel with a mineral coating under a load of 1 kg, magnification 50×.

The dynamics of wear losses presented in Table 4 show that the wear resistance of wheel samples with mineral alloying technology in combination with localized electric spark hardening is 2.4 times higher than that of wheel samples without such treatment. These results are confirmed by a comparison of the wear of wheel rollers and rail check rollers after the completion of the test: the wear of wheel rollers with a mineral coating is 0.244 g, and the rail check rollers are 0.232 g. At the same time, the wear of wheel rollers without a coating is 0.589 g, and the rail check rollers are 0.235 g. Based on the wear of the wheel roller with a mineral coating over the entire test period, the approximate estimate of the duration of coating abrasion per friction path is 3.2×10^{-5} g/m.

It should be noted here that the wear of rail check rollers working in pairs with rollers of wheels with a mineral coating (0.232 g) is practically no different from the wear of rail rollers working in pairs with rollers of wheels without a coating (0.235 g). The wear resistance of the rail roller in both tests is almost the same — 20.374×10^5 m/g and 20.589×10^5 m/g. Thus, the tests showed that the use of mineral-coated wheel rollers in the friction pair does not affect the wear of the rail counter rollers, since it does not lead to an increase in wear. In general, the test results also showed that the friction pair with mineral-coated wheel rollers is characterized by a significant decrease in the total wear of the "wheel roller + rail counter roller" samples — 42% less compared to the friction pair without a coating.

Visual inspection of the condition of the friction surfaces of the rollers and the rail counter rollers working in pairs with them at the end of the test after $6\cdot10^4$ cycles showed that the surface of the coated samples was uniformly worn with remnants of the original relief and small annular grooves. On the surface of the counter rollers, there were small scratches with local burrs and nicks. At the same time, the surface of the uncoated rollers is characterized by a smoothed relief with traces of deeper annular grooves, shallow scratches, and local nicks. On the surface of the counter rollers working with them, there are more pronounced traces of scratches and nicks with areas of transfer of the material of the wheel rollers to it, as well as weak traces of seizure and tearing of the metal of the rollers.

The radical increase in the wear resistance of the samples can be explained by the peculiarities of the formation of the surface layer created by the technology of mineral coatings and the causes of damage to the rails. Traditionally, the main concept of rail degradation is associated with the formation and evolution of defects that reduce the strength of parts and structures experiencing mechanical loads [16, 28 – 29]. This concept is based on studies of the physical nature of the accumulation and evolution of the structural-phase states of the surface layers of rails during long-term operation. Currently, a large amount of experimental material has shown that during the operation of rails, a large number of microcracks, micropores, and pittings are formed in the surface sublayer [16, 28 – 29], and the operation of the rails is accompanied by a transformation of the dislocation substructure [28]. One of the results of the research is the conclusion that with a further increase in operation, on the one hand, the hardness of the surface layer of rail steel increases, and on the other hand, the number of defects increases [28]. Therefore, the main type of damage to rails during operation is contact-fatigue defects, the origin of which is not associated with the low purity of the steel for non-metallic inclusions but with the development of destruction processes of the surface layer of the metal of the rail head (the upper element of the rail) [29].

During the process of creating mineral layers, microcracks, defects, and surface irregularities are filled with ultrafine particles, which, as a result of ultrasonic exposure, end up inside the surface layer in existing and/or previously created microcavities [17]. As a result of such "cold" processing, a modified layer with high hardness and wear resistance is formed [18 – 22]. Subsequent pressing leads to an increase in the density of defects in the surface layers,

Table 4. Results of comparative tests for the wear resistance of samples made of wheels made of CT2sp steel with a mineral treatment and samples of wheels made of CT2sp steel without a treatment.

Quantity	Wheel samples without mineral doping technology	Wheel samples with mineral doping technology	
	Measured values	Measured values	Relative change, %
Wear loss of wheel roller, $(m/g)\times10^5$	4.053	9.809	+142
Average wear rate of wheel roller, $(g/m)\times10^{-5}$	0.247	0.102	−59
Wear loss of the wheel roller during the entire test, g	0.589	0.244	−59
Wear rate of rail roller, $(m/g)\times10^5$	20.374	20.589	+1
Average wear rate of rail roller, $(g/m)\times10^{-5}$	0.0491	0.0486	−1
Wear loss of the rail roller during the entire test, g	0.235	0.232	−1
Total wear loss of a friction couple, g	0.824	0.476	−42

creating compressive stresses that prevent the development of surface cracks [17].

Consistent inclusion of electro spark machining in the technological process can affect the thermal decomposition of serpentine (as a component of the mixture) and the formation of harder phases compared to the original serpentine [30]. It can also be assumed that the finely dispersed material of the serpentine decomposition products (apparently largely amorphized) fills micropores, microcracks, various defects, and vacancies on the surfaces of the friction unit, which leads to their strengthening and a significant increase in wear resistance [31].

By varying the parameters of the electro spark hardening process, it is possible to control the content and properties of the serpentine decomposition products and, accordingly, influence the tribological parameters of the surface. By adjusting the properties of the modified surface to the parameters of the counter rollers, it is possible to minimize the wear of the wheel-rail tribosystem, which was done in this article.

Of course, these assumptions require further studies of the defects of the surface layer of rails hardened using mineral coating technology.

4. Conclusions

A comparative study of the wear resistance of samples made of wheels made of ordinary quality carbon steel grade CT2sp with a surface layer created using ultrafine mineral particles (quartz, serpentine, tungsten carbide) using mineral coating technology and wheel samples made of uncoated CT2sp steel showed the following:

1. The modification increased the wear resistance of the samples by 2.4 times (compared to uncoated samples), which led to a significant reduction in their wear (a decrease of 59%) after $6\cdot10^4$ test cycles. The approximate estimate of the duration of coating abrasion per friction path is 3.2×10^{-5} g/m at a contact pressure of 752 MPa and a rotation speed of 195 rpm, without lubrication.

2. The wear of the counter rollers, which worked in tandem with the rollers of wheels with a mineral coating, is practically no different from the wear of the rail rollers, which worked in tandem with the rollers of wheels without a coating, which can help minimize the wear of the "wheel-rail" tribosystem.

The tests showed the practical possibility of adjusting the properties of the modified roller surface to the parameters of the counter rollers to minimize wear of the wheel-rail contact pair, which can be used for the operation of railway transport operating in conditions of abrasive dust, high humidity, and other aggressive environments.

References

1. G. Zhang, R. Ren, Study on typical failure forms and causes of high-speed railway wheels, Eng. Fail. Anal., 105 (2019) 1287–1295.
2. G.L. Akkerman, S.G. Akkerman, Curved sections of track and trains with a car body tilt, Herald of the Ural State University of Railway Transport, 1 (2022) 24 – 30. (in Russian)
3. B. Dirks, R. Enblom, Prediction model for wheel profile wear and rolling contact fatigue, Wear 271 (2011) 210 – 217.
4. T.G. Pearce, N.D. Sherratt, Prediction of wheel profile wear, Wear 144 (1991) 343 – 351.
5. E. Magel, J. Kalousek, Designing and assessing wheel/rail profiles for improved rolling contact fatigue and wear performance, Proc. IMechE, Part F: J Rail and Rapid Transit 231 (2017) 805 – 818.
6. U. Olofsson, Y. Zhu, S. Abbasi, et al., Tribology of the wheel-rail contact — aspects of wear, particle emission and adhesion, Vehicle System Dynamics; Special Issue: State of Art Papers (2013) 1091–1120.
7. S.M. Zakharov, Guidelines to best practices for heavy haul railway operations: wheel and rail interface issues, IHHA, Virginia Beach, USA, 2001, 485 p.
8. U. Olofsson, Y. Lyu, Open system tribology in the wheel–rail contact — a literature review, Appl. Mech. Rev. 6 (2017) 060803.
9. U. Olofsson, Adhesion and Friction Modification. Wheel-Rail Interface Handbook, Woodhead Publishing, Cambridge, UK, 2009, 856 p.
10. W.J. Wang, R. Lewis, M.D. Evans, et al., Influence of Different Application of Lubricants on Wear and Pre-existing Rolling Contact Fatigue Cracks of Rail Materials, Tribol. Lett. 65 (2017) 58.
11. T. Bai, J. Xu, H. Zhu, et al., Investigation into the wear evolution and fatigue crack propagation behaviour of rails subjected to laminar plasma discrete quenching and tempering treatment, Wear 554 – 555(2024) 205470.
12. A.V. Aborkin, V.E. Vaganov, A.N. Shlegel', I.M. Bukarev, Effect of Laser Hardening on Die Steel Microhardness and Surface Quality, Metallurgist 59 (2015) 619 – 625.
13. A.I. Gorunov, Laser hardening of 4X5MФС die steel, Russ. Eng. Res. 36 (2016) 206 – 208.
14. C-L. Liang, K-L. Lin, The microstructure and property variations of metals induced by electric current treatment: A review, Materials Characterization 145 (2018) 545 – 555.
15. C-C. Shu, C-L. Liang, K-L. Lin, Electro-work hardening of metals induced by the athermal electromigration effect, Mater. Sci. and Eng.: A 772 (2020) 138689.
16. S.Y. Zhang, M. Spiryagin, H.H. Ding, et al., Rail rolling contact fatigue formation and evolution with surface defects, Int. Journal of Fatigue 158 (2022) 106762.
17. S.V. Kislov, V.G. Kislov, A.V. Skazochkin, G.G. Bondarenko, A.N. Tikhonov, Effective mineral coatings for hardening the surface of metallic materials, Russ. Metall. (Metally) 2015 (2015) 558 – 564.
18. A.V. Skazochkin, G.G. Bondarenko, S.V. Kislov, Research of Tribological Features of Steel Surface by Creating Mineral Coatings, Journal of Eng. Sci. and Technol. Review 11 (2018) 138 –143.
19. A.V. Skazochkin, G.G. Bondarenko, V.B. Perov, Study of tribological parameters of rail steel 76 modified with ultrafine mineral particles, Metals 4 (2024) 75 – 84. (in Russian)
20. S.V. Kislov, V.G. Kislov, P.V. Balash, A.V. Skazochkin, G.G. Bondarenko, A.N. Tikhonov, Wear resistance of a metal surface modified with minerals, IOP Conf. Ser.: Mater. Sci. Eng. 110 (2016) 012096.

21. A. V. Skazochkin, G. G. Bondarenko, P. Zukowski, Research of Surface Wear Resistance of Aluminum Alloy Modified with Minerals using Sclerometry Method, Devices and Methods of Measurements 10 (2019) 263 – 270.
22. A. V. Skazochkin, Abrasive wear of metal surface modified with mineral particles, Conf. Ser.: Mater. Sci. Eng. 996 (2020) 012023.
23. Steel CT2, Available online. (accessed 1 August 2025). (in Russian)
24. Chemical composition of steel E76HF, Available online. (accessed 1 August 2025). (in Russian)
25. K. L. Johnson, Contact Mechanics, Cambridge University Press, Cambridge, UK, 1985, 462 p.
26. A. V. Skazochkin, A. S. Useinov, S. V. Kislov, Surface hardening of titanium alloy by minerals, Letters on Materials 8 (2018) 81 – 87. (in Russian)
27. A. V. Skazochkin, G. G. Bondarenko, P. Zukowski, Features of measuring the hardness of a metal surface modified with ultrafine particles of minerals, Devices and Methods of Measurements 11 (2020) 212 – 221.
28. V. E. Gromov, Yu. F. Ivanov, R. S. Qin, et al., Degradation of structure and properties of rail surface layer at long-term operation, Materials Science and Technology 33 (2017) 1 – 6.
29. O. A. Peregudov, K. V. Morozov, V. E. Gromov, et al., Formation of internal stress fields in rails during long-term operation, Russ. Metall. (Metally) 2016 (2016) 371 – 374.
30. G. Heinicke, Tribochemistry, Akademie-Verlag, Berlin, 1984, 495 p.
31. Y. Jin, H. Yang, F. Wang, C. Minfray, S. Li, Phase structure and lubricity of in-situ generated protective layer on worn metal surfaces in presence of $Mg_6Si_4O_{10}(OH)_8$, Proceedings of the World Tribology Congress III. World Tribology Congress III, Volume 2. Washington, D.C., USA. September 12–16 (2005) 449 – 450.