Nanopowders of Different Chemical Composition Added to Industrial Lubricants and Their Impact on Wear Resistance of Steel Friction Pairs

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Abstract: The authors have previously proposed and tested a method for increasing the wear resistance of heavy-loaded friction pairs by saturating industrial lubricants with the metallic nanopowder of the friction pair’s component that has a lower hardness. To confirm the effectiveness of this concept, this paper presents the results of experimental investigations into the tribological characteristics of two medium carbon steels (rail steel K74 and structural steel 20) during sliding friction. Friction surfaces lubricated with compositions based on the Bio Rail industrial lubricant were saturated with nanopowder additives of copper, carbon, and magnesium alloy, as well as K74 and 20 steels. The research findings indicate that lubricants saturated with nanomaterials of K74 and 20 steels help achieve the highest wear resistance, as compared to lubricants based on pure grease and lubricating compositions based on copper, magnesium alloy and carbon powders. The test results confirmed that the mean friction coefficient of the rail steel remained at the level of 0.25 for three hours of operation, which is optimal for the “wheel–rail” friction pair. The proposed method of manufacturing lubricating compositions can be used to improve the efficiency of lubrication of railway rails and rolling stock wheels.

Keywords: lubricating composition; wear; electrochemical corrosion; friction pair wheel–rail

1. Introduction

Modern transportation technologies require lubricants that provide a high wear resistance of machine parts, ensuring a significant reduction in the consumption of energy, fuel and lubricants. In recent years, research has largely focused on improving the service qualities of industrial lubricants using various additives, particularly those based on nanomaterials, as evidenced by numerous scientific publications and patents for relevant inventions [1–7]. When added to lubricants, nanomaterials can change their service properties dramatically. Although the volume content of such additives in lubricating compositions is low enough (from 0.1 to 10 wt.%, [8–14]), their presence has a significant impact on such complex characteristics as wear resistance or friction coefficient, which is of particular note. Apart from the volume content of particles, the nature of this impact naturally depends on the particles’ dispersion, morphology, chemical composition, and mechanical properties. At the same time, many physical properties of such lubricating compositions (density, adhesion, resistance to environmental influences, operating temperature range, etc.) undergo minor changes.
As regards the impact caused by nanomaterial additives on the wear of friction pairs made of metallic materials under conditions of lubrication, four major mechanisms of such impacts have been distinguished to date [3,15,16]. The first is associated with the active centers of the nucleation and propagation of specific nanocrystalline structures in the form of microcoatings that occur on defects of friction surfaces. In addition, this process is controlled by the energy released during friction [17,18]. As a result, a very thin film is formed on the contact surface, which consists mainly of ultrafine particles of the material. The surfaces of the parts have a certain micrelief and the actual contact occurs on a relatively small area, even if the friction pair’s components are optimally shaped. This film has a huge number of pores, in which the lubricant is retained. Due to this film, the actual contact area of parts increased tenfold and the contact stress level decreased significantly, thereby protecting friction surfaces from wear. This film was proven to be formed due to lubricants, the molecules of which include the atoms of low-hardness metals, such as copper, tin, lead, zinc, aluminum, silver, gold, etc. Therefore, salts of fatty acids or complex compounds of polyvalent metals are often used as additives [1,3,15].

Metal nanopowders of different dispersions used as additives have also attracted the attention of researchers, since such methods for creating metal-containing additives are technologically simpler and often cheaper. Apart from nanopowders of soft metals, the compounds of chromium, nickel, iron, cobalt, and tungsten, as well as non-metallic materials of natural or artificial origin (graphite, diamond, silicates, etc.), are also used for this purpose [8–10,19–21], these being the materials with sufficiently high hardness. This has a significant impact on the processes that occur in the contact zone of parts and, according to researchers, allows using other mechanisms for enhancing wear resistance.

One of them is rolling over solid, rather large particles [21]. As a result, sliding friction turns to rolling friction. This mechanism is rarely realized in its pure form. It may manifest itself when the powder particles’ hardness exceeds that of the friction surfaces, and their volume content in the lubricating composition is high enough. In this case, contact stresses may be relatively small, given the large number of powder particles, and, therefore, will not lead to significant plastic deformation and the destruction of particles.

Another two mechanisms (cutting of protrusions and filling of depressions) are associated with nanosized particles present in the contact zone, the hardness of which is no less than that of the parts’ surfaces. In this case, a solid servovite film is not created, whereas solid particles intensify the plastic deformation of irregularities upon the sliding of the friction surfaces, which leads to the occurrence of a finely dispersed (subgranular) structure in the surface layers of the parts. Powder particles are strongly deformed, fine-tuned, and they become elements of the subgrain structure [11,22–24]. Some of them fill microcavities on the friction surfaces, due to which the overall surface roughness decreases, and the contact area increases significantly. A structure of this kind enhances the material strength, including hardness, fracture toughness and crack resistance, due to which the wear resistance of friction pairs increases.

The course of these processes naturally depends on the compatibility of the friction pairs’ materials, lubricants and nanopowders, used as additives. Therefore, to establish the general regularities in these physical phenomena, further research is required.

The authors have previously conducted experiments on the friction and wear of rail steel using industrial lubricants for rails and a relevant lubricating composition saturated with the nanomaterial of the same rail steel [10]. Based on the analysis of the findings, the authors came to the following conclusion: lubricating compositions saturated with nanomaterials made of the friction pair’s component that has a lower hardness may be good at increasing the wear resistance of parts and ensuring the optimal friction coefficient for the open, highly loaded friction pairs.

To verify this concept, this paper analyzes the research findings on the wear resistance of two steels under conditions of friction using industrial lubrication, as well as lubricating compositions based on it with additives of nanopowders of various materials.
2. Materials and Methods

In our wear experiments, we used the 2070 CMT-1 test rig (serially manufactured by the company RSCVM, the Russian Federation) with additional equipment for the automatic recording of the friction moment and force, temperature in the contact zone and specimen wear, as well as software for the automated processing of experimental data.

Specimens for wear tests [10] were made of two steel grades: specimens from rail steel K74 were made from the middle part of the type P50 rail head, and specimens from industrial steel 20 were made from bars with a square cross-section of 20 × 20 mm². Wheel steel was used to manufacture the counterbody (50 mm-diameter disk with a thickness of 10 mm). The disks were cut from wheel rims that were put out of service.

The specimen loading scheme during friction and wear tests is given in [10]. To determine the main mechanical characteristics of steels (elasticity modulus \(E\), yield strength \(\sigma_{ys}\) and conventional ultimate strength \(\sigma_{us}\)), specimens with a thickness of 3 mm were used, which were made from the relevant parts of the rail and the wheel rim. The Bi-00-201 servo-hydraulic test rig (manufactured by BiSS, Bangalore, India) was used for tensile tests. Similarly, the mechanical properties of the materials used for manufacturing nanopowders—M2 copper and MA2 magnesium alloy—were determined. Sheets with a thickness of 3 mm from the specified materials were used for the production of tensile specimens. The chemical composition and main mechanical properties of steels and materials for producing nanopowders (except carbon) are given in Table 1.

Table 1. Chemical composition and basic mechanical characteristics of test materials.

| Materials              | Chemical Composition (by Main Components) | \(E\), GPa | \(\sigma_{ys}\), MPa | \(\sigma_{us}\), MPa |
|------------------------|-------------------------------------------|-----------|---------------------|---------------------|
| Steel K74              | C—0.57%, Si—0.32%, Mn—0.94%, Fe—base     | 211       | 740                 | 920                 |
| Steel 20               | C—0.18%, Si—0.19%, Mn—0.41%, Cr—0.05%, Fe—base | 210   | 250                 | 435                 |
| Steel 2                | C—0.58%, Si—0.34%, Mn—0.76%, Fe—base     | 212       | 845                 | 985                 |
| M2 copper              | Fe—0.04%, Ni—0.08%, Sn—0.02, Cu—base      | 117       | 116                 | 210                 |
| MA2 magnesium alloy    | Al—4.32%, Mn—0.32%, Zn—1.16%, Mg—base    | 48.8      | 135                 | 230                 |

The specimen wear was determined using a contactless inductive displacement sensor of the ZXE type (manufactured by OMRON Corporation, Kyoto, Japan) in the smallest cross-section of the specimen.

Tests were conducted under the following conditions: rotation frequency—300 rpm; normal pressure force—555 N; continuous operation time—3 h; the contact stress level was equal to 2.83 MPa. The friction coefficient was determined as \(\mu = \frac{M}{dN}\), where \(M\) is the friction moment; \(d\) is the counterbody disc diameter; \(N\) is the normal pressure force.

The microhardness of the specimen’s working part was measured before the start of the experiment and after its completion. Hardness measurements (according to Rockwell, HRC scale) were made using the COMPUTEST SC portable hardness tester manufactured by ERNST (Emdoor Group, Shenzhen, China). The conical diamond indenter with an angle of 110° at the top took up the load of 49 N. In the initial state, the ratio of the counterbody’s hardness (HRC = 35.3) to the mean hardness of the steel was found to be 1.1 for specimen from the rail steel and 1.14 for specimens from steel 20.

The wear of steel specimens was studied under conditions of friction with lubrication. All friction regimes are listed in Table 2 (the + sign means that experiments were conducted out).
Table 2. Friction regimes investigated.

| Specimens’ Material | Friction Regimes | Friction Regimes | Friction Regimes |
|---------------------|------------------|------------------|------------------|
|                     | Bio Rail Oil     | Bio Rail Oil +   | Bio Rail Oil +   |
| Steel K74           | +                | Nanopowder of    | Nanopowders of   |
|                     |                  | K74 Steel        | Steel 20, Copper, |
|                     |                  |                  | Carbon and Magnesium Alloy |
| Steel 20            | +                | –                | +                |

We used one-time lubrication, with two drops of pure lubricant or lubricating composition applied to the specimen’s contact surface. At present, the Bio Rail lubricant manufactured by AIMOL [25] is used for lubricating rails of the South-Western Railway of Ukraine. Therefore, it was chosen for this research.

Currently, there are many technologies and methods for the industrial production of nanopowders, the most common of which are gas-phase synthesis, the electric explosion of conductors, cathodic sputtering, and mechanical and ultrasonic dispersion [11,21,22,26]. Depending on the technology and equipment used, the particle size can differ tenfold.

In this research, the method for the synthesis of nanoparticles, the electric-spark dispersion (ESD) of metal granules in a 40% alcohol liquid medium was used [26].

A high-intensity impulse current passed through a layer of metal granules causes their destruction, melting and even evaporation. Since this process takes place in a liquid medium, two types of microparticles are formed upon rapid cooling (microparticles of metal and its oxides), which are quite different in size, morphology, and chemical composition. Particles measuring from several tens to hundreds of nanometers are crystallized from the melt, and their shape is close to spherical. As a result of the rapid cooling of metal vapors, much smaller particles are formed, which often have faces typical of crystalline formations. The ratio of nano- and ultradispersed particles in the mixture depends on the current intensity, frequency and duration of pulses, and the liquid type [27–29]. Thus, for instance, Cu, CuO and Cu₂O particles with an average size of 300 to 15 nm are formed when copper granules are processed, and the proportion of smaller particles increases with an increase in the peak power [29].

This is a very promising method because it combines temperature-deformation processing in the course of particle formation with high technological effectiveness. Depending on the parameters of the technological process, the size of the obtained particles can vary within a wide range—from a few nanometers to several microns.

A setup for the realization of the above method was created and operated at the National University of Life and Environmental Sciences of Ukraine (Kyiv, Ukraine) for several years, and its schematic diagram is given in [26]. The production capacity of the setup allows obtaining ultradispersed powders of various metals and alloys in sufficient amounts.

Granules of test materials were made of mechanical processing waste (shavings) during the production of specimens. Nanopowders of all metals were obtained under the same operating conditions of the setup. The carbon powder (GK1 pencil graphite) was not crushed additionally.

The suspensions obtained as described above were kept in a fume hood until the liquid evaporated completely. Dried metal nanopowders had a dispersion of 100, . . . , 300 nm. The carbon powder had a dispersion of 6–40 µm. The content of additives in all variants of lubricating compositions (see Table 2) was approximately 10 wt %.

3. Results

When investigating the friction and wear of metallic materials in laboratory conditions, the dependence of wear on the working time usually has the following form (Figure 1) [30]. If the difference between the hardness of the counterbody and the test material is not too big, then three characteristic areas can be distinguished on this curve. The high wear rate at the
initial stage of operation (zone I) is due to the significant local plastic deformations of the specimen surface (which are greater on the specimen and much lower on the counterbody), since the contact zones have a certain roughness. These processes help reduce the specimen roughness. As a result, the overall level of contact stresses decreases, while their distribution on the contact surface becomes uniform. A certain part of protrusions is cut off, and material particles are removed from the contact zone.

Figure 1. Typical dependence of wear on the working time (explanation of Zones I, II, III are given in the text).

The running-in of the part’s surface is followed by the uniform wear stage (zone of comfortable contact II), which is characterized by slight changes in the damage accumulation rate. Zone II can be quite long depending on the test conditions. Zone III on the graph corresponds to the critical accumulation of damage and the actual fracture of the part’s surface.

The running-in stage (zone I), at which the parts undergo big changes, is short enough. Given this, we limited the duration of experiments to three hours.

Figure 2 shows wear diagrams of the steel under the selected conditions of friction with lubrication (see Table 1). Parameter $\Delta h = h_0 - h$, which characterizes the degree of wear, represents the difference between the initial and current size of the specimen in the smallest cross-section (see Figure 1 in [10]).

Figure 2. Wear diagrams for specimens made of steel 20 (a) and steel K74 (b) under different conditions of friction with lubrication: (a) 1—lubricant; 2—lubricant + C; 3—lubricant + Cu powder; 4—lubricant + MA2 powder; 5—lubricant + steel powder 20; (b) 1—lubricant; 2—lubricant + K74 steel powder.

In the process of friction, specimens were heated from 50 to 70 °C. In a certain way, this could affect the accuracy of wear measurements by a non-contact sensor. However, due to the small specimen size, its thermal expansion can be neglected. Upon the completion of
experiments, the control measurements of specimen sizes showed that the measurement errors did not exceed 4%.

The analysis of the findings (see Figure 2) allowed us to make a number of important conclusions. Nanopowders of steel K74, steel 20, magnesium alloy, and carbon added to the Bio Rail industrial lubricant help reduce the wear of steel friction pairs under the given experimental conditions, as compared to the lubrication based on pure lubricant. The lubricating composition with copper powder (curve 3 in Figure 2a) is an exception. Lubricating compositions saturated with nanopowders of the test steels (see curve 5 in Figure 2a and curve 2 in Figure 2b), as well as the composition based on the MA2 alloy powder (see curve 5 in Figure 2a), proved to be most effective for enhancing the wear resistance of steel friction pairs. The given data confirm the main conclusion [10] that the nanomaterial from the friction pair’s component that has a lower hardness should be used as a wear-resistant additive to industrial lubricants.

An Important parameter of the friction pair’s operation is the friction coefficient. The energy parameters of machines and mechanisms depend on its value in a certain way. It is obvious that the wear resistance of parts increases when friction decreases. However, it should be borne in mind that reducing the friction coefficient below a certain value is inadmissible for some types of friction pairs. Thus, for the wheel–rail pair, the optimal friction coefficient is in the range of 0.3 ... 0.35 on the rolling surface of the rails’ head. On the side surface of the rails’ head, it is in the range of 0.2 ... 0.25 [31]. Such values of \( f \) are optimal from the perspective of the traction forces and traffic safety.

Graphs showing changes in the friction coefficient depending on the test conditions are presented in Figure 3a. The initial values of \( f \) are slightly different for all specimens. This is due to the presence of still undeformed additive particles and some differences in the specimen roughness. To facilitate the analysis of various additives that cause changes in the friction coefficient, Figure 3b presents the data obtained in relative values \( f/f_0 \), where \( f_0 \) is the initial value.

![Graphs showing changes in the friction coefficient depending on the test conditions](image)

**Figure 3.** Variation of the friction coefficient over time in absolute (a) and relative (b) values: 1—steel 20 + lubricant + Mg; 2—steel K74 + lubricant; 3—steel 20 + lubricant + C; 4—steel 20 + lubricant + Cu; 5—steel 20 + lubricant; 6—K74 steel + lubricant + K74 steel powder; 7—steel 20 + lubricant + steel 20 powder.

Previous studies have shown that the friction coefficient increases rapidly and reaches a value of 0.73 under conditions of dry friction. This leads to the appearance of defects on the specimen surface, which are associated with significant plastic deformation of the surface layers. Similar processes occur with significant wheel slippage relative to the rails. Changes in the friction coefficient during lubrication are completely different. When lubricating a specimen from the rail steel with pure lubricant, it slightly decreases from the
The initial value of 0.22 to 0.15 (due to the specimen heating and a decrease in the lubricant viscosity), and then increases to 0.3 gradually. The nature of the change in $f$ and its rather high value after three hours of operation indicate that the lubricating film is gradually destroyed under the given test conditions.

The K74 steel nanopowder added to the lubricant promotes the rapid stabilization of the friction coefficient at the optimal level of 0.25, indicating that this additive can be used to enhance the wear resistance of railway rails.

For steel 20, the lowest $f$ after three hours of operation was recorded for the composition with magnesium alloy. Adding the steel 20 nanopowder to the lubricant also gives good results in stabilizing the friction coefficient at the level of ~0.25. The addition of carbon slightly increases the lubricating film durability. For the composition with copper powder, the nature of $f$ variation (see Figure 3b) confirms that, under the given test conditions, its use does not give positive results.

We note that the main goal of this research was to find out whether nanomaterials of various alloys manufactured as described can be used to enhance the wear resistance of heavily loaded “wheel–rail” friction pairs. Such friction pairs are characterized by high contact stresses and significant slippage. Under such conditions, the morphology and even the size of powder particles (to a certain extent) will affect friction and wear only at the initial stage of the friction pair’s operation. Due to significant plastic deformation and the destruction and grinding of particles, their initial parameters will not be of significant importance at subsequent stages of operation. This is illustrated by the behavior of curves in Figure 3a. The initial coefficients of friction (COF) for various additives are quite different, which is obviously due to the different sizes and morphologies of the powders. However, the COF decreases significantly during the first hour of operation. Differences in the COF during further operation, in our opinion, are related to the compatibility of the lubricant, additive and material of the friction pair. To confirm these assumptions, detailed physical research is required.

4. Discussion

As already mentioned [10,11,22], in the process of friction between rough surfaces, the hardness of the surface layers of parts changes due to local plastic deformation. This phenomenon is directly related to the wear intensity; however, no stable correlations of these processes have been found, since experimental data are still insufficient and not systematized. A possible way of establishing certain correlations is a compatible analysis of data on the wear intensity, changes in surface hardness of specimens and parameters that characterize the level of damage to the material structure.

For this purpose, hardness measurements and the evaluation of damage caused to the specimen surface layers were analyzed (Figure 4). For convenience, hardness measurements of the specimen working surface upon test completion are given in the relative values of $H/H_0$, where $H_0$ is the specimen hardness before the tests (averaged data based on the results of 30 measurements are given).
As a result of plastic deformation due to high contact stresses, the surface layers of the specimen working part are damaged and their hardness changes, and the presence of the so-called third body (lubricants, additives, lubricating compositions, etc.) in the contact zone significantly affects the course of these processes. To assess the level of damage to the microstructure of the specimen material, the technique developed by the State Standard of Ukraine [32,33], which determines the level of material damage based on the hardness values’ dispersion parameter, proved to be very effective.

The physical substantiation of this technique is as follows: the dispersion of the mechanical properties is inherent in all materials, and the degree of their dispersion depends mainly on their structural state. Therefore, parameter $m$ of the Weibull distribution law, which describes the material hardness dispersion, can be used to estimate changes in the structural state of the surface layers of the specimen material after service. This parameter represents the material homogeneity coefficient, it can be determined by the Gumbel formula, which, when using the Rockwell hardness numbers, has the following form:

$$m = 0.4343 \frac{d(n)}{\ln H_i - \ln H_m} \left( \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{d(n)} \right)^2 \right)^{-\frac{1}{2}},$$

where $d(n)$ is determined by nomogram [29] depending on the number of $n$ measurements; $H_i$ is the hardness value according to the $i$-th measurement; $\ln H_m$ is the mean value of the hardness logarithm based on the $n$ measurement results. According to standard [32], the homogeneity coefficient $m$ was determined based on the results of 30 measurements. In this case, $d = 1.1124$. Coefficient $m$ was determined to the accuracy of $\pm 0.05$.

A higher homogeneity coefficient corresponds to a low dispersion of microhardness characteristics and, accordingly, a better microstructure organization of the material surface layers. This technique has already been tested with a similar purpose in [10] and, therefore, the authors find it appropriate to be used in this research.

Since in our case the initial homogeneity coefficient and mean hardness (based on 30 measurements) were slightly varied for different specimens (since they were cut from different parts of the rails’ head), the microhardness measurements and calculations of damage caused to the material structure were presented in relative values for further analysis: $\Delta H = \frac{H_t - H_0}{H_0} \cdot 100\%$ and $\Delta m = \frac{m_t - m_0}{m_0} \cdot 100\%$, where index 0 corresponds to the initial (conditionally undamaged) state of the material. Microhardness measurements to
determine the relative values of $\Delta H$ and $\Delta m$ were made with the COMPUTEST portable hardness tester. The results of the analysis are summarized in Table 3.

**Table 3.** Variation of the mean hardness of the specimen working part and the homogeneity coefficient under different conditions of friction.

| Steel       | Conditions of Friction | Variation of the Mean Hardness, $\Delta H$, % | Variation of the Homogeneity Coefficient, $\Delta m$, % |
|-------------|------------------------|-----------------------------------------------|---------------------------------------------------|
| Steel K74   | Dry friction           | +8.5                                          | 72                                                |
|             | “Bio Rail” lubricant    | +9.8                                          | 31                                                |
|             | “Bio Rail” lubricant + steel K74 nanopowder | +14.7                                       | 29                                                |
| Steel 20    | Dry friction           | +13.6                                         | 67                                                |
|             | “Bio Rail” lubricant    | +13.9                                         | 34                                                |
|             | “Bio Rail” lubricant + C | +1.3                                           | 58                                                |
|             | “Bio Rail” lubricant + M2 copper nanopowder | +4.2                                          | 63                                                |
|             | “Bio Rail” lubricant + MA2 magnesium alloy nanopowder | +31.6                                       | 32                                                |
|             | “Bio Rail” lubricant + steel 20 nanopowder | +16.4                                         | 32                                                |

The above data indicate that the material surface layers are damaged, and their hardness increases upon friction. The friction conditions affect these processes significantly. Under dry friction, the degree of damage to materials based on the evaluation of changes in the homogeneity coefficient is the greatest at $-72$ and $67\%$, while the hardness due to the surface strain hardening increases by only $8.5$ and $13.6\%$ for steel K74 and steel 20, respectively. Lubrication with pure lubricant significantly reduces wear and damage to the specimen surface, while increasing hardness. Adding nanomaterials to the lubricant affects the specified characteristics appreciably. For steel K74, the lowest damage and, at the same time, the greatest hardening is observed upon friction using the lubricating composition “Bio Rail” lubricant + steel K74 nanopowder (see Table 3). For steel 20, a similar lubricant composition also gives good results. Moreover, given the resulting almost complete lack of wear (see Figure 2), we can conclude on the obvious advantage of lubricating compositions based on nanopowders of the friction pair’s component that has a lower hardness. This conclusion naturally applies to the test materials only.

For steel 20, the lowest wear was observed when using the lubricating composition based on MA2 magnesium alloy powder, and the highest—for the composition based on copper powder. Many researchers believe [9,34–36] that additives of copper-based nanomaterials are the best for lubricants, because they lead to the formation of a servovite film on the part’s surface, which helps reduce wear. However, in our case, the greatest wear of the specimen made of steel 20 was recorded when the composition based on M2 copper powder was used. This indicates that, under the given test conditions, a continuous servovite film is not created on the specimen surface. This may be due to the fairly large size of the powder particles. Similar results were obtained in [11,22], where copper powders with a dispersion of 80–120 nm were used as an additive to the industrial lubricant. The authors of these papers present the findings of complex metallophysical studies. According to them, a thin interfacial layer is created instead of a servovite film. This interfacial layer contains fragments of the base metal and deformed copper particles, as well as iron and copper oxides. A rather high homogeneity coefficient indicates significant damage to the specimen surface, which may be due to the different hardness of the interfacial layer’s components.

When comparing the obtained results with literature data, one should take into account the different conditions of conducting experiments—different installations and methods of research, lubricants, methods of manufacturing additives, sizes and morphology of particles, chemical composition of additives, etc. It is obvious that the results obtained
under similar conditions should be compared. Therefore, the obtained experimental results may not coincide with the known literature results. In this work, the same samples, test method, industrial lubricant and method of manufacturing nanopowders were used. These results, in our opinion, clearly indicate the effectiveness of nanoadditives, which are made of a friction pair metal with lower hardness.

For steel 20, the best results were obtained when magnesium alloy powder was used as an additive. As for carbon, its effect is almost negligible when mixing with oil.

The efficacy of using lubricant compositions based on nanopowder additives depends on many factors, the main of which is the friction pair type. For the open load-bearing friction pairs of the wheel–rail type, adding a nanomaterial to the industrial lubricant has shown promising results in increasing wear resistance to a significant extent, while achieving the optimal friction coefficient. Another advantage of using the rail steel nanopowder as a wear-resistant additive to industrial lubricants is its moderate cost, since the raw material for its manufacture is waste that remains in the process of rail manufacture.

As regards using nanopowders of other metals or alloys (for example, copper, brass, bronze) as additives to industrial lubricants, one should consider the possible significant difference between the electrochemical potentials of the part’s material and the additive. For the open friction steel pairs (for example, the wheel–rail pair), using such additives is unacceptable, because it will lead to corrosion of the contacting parts in the open air.

For the closed friction steel pairs that work in a lubricating medium, nanopowders used as additives can be made of various metals and alloys, as well as some non-metallic materials. However, the efficiency of such additives should be determined experimentally under conditions as close as possible to the operating conditions of the parts.

5. Conclusions

The main regularities in the impact of nanopowders of different chemical composition added to the Bio Rail industrial lubricant on the tribological characteristics of two medium carbon steels were found in this paper. Nanopowders of copper, magnesium alloy, carbon, and test steels were used as additives. For both steels, an increase in wear resistance was recorded when nanopowders were added to the lubricant, except for the nanopowder based on copper.

For the K74 rail steel, the best results in terms of enhancing wear resistance and providing for the optimal friction coefficient are attained when the nanopowder of the same steel is used as an additive to the Bio Rail lubricant. After three hours of operation, which corresponds to the friction path of 8.5 km, the specimen wear did not exceed 0.0015 mm. The friction coefficient reached its optimal value of ~0.25 for the wheel–rail pair after the first hour of operation, and remained almost unchanged subsequently. At the same time, the specimen surface hardness increased by 14.7%.

For structural steel 20, the lowest wear rates were recorded when lubricant additives based on the nanomaterials of steel 20 and magnesium alloy MA2 were used. In the latter case, the friction coefficient was the lowest. Lubricant additives based on the GK1 graphite granules had an insignificant effect on the tribological parameters. The worst results in terms of wear were attained for the lubricating composition based on the M2 copper powder, which is obviously due to the rather large size of the powder particles.

The joint analysis of the experimental data on the wear kinetics, hardness variation and damage accumulation on the specimen surface layers makes it possible to establish certain correlations between these parameters. In combination with detailed physical studies, this will allow for an adequate physical explanation to a phenomenon of increasing wear resistance of steel friction pairs when using lubricating compositions based on the additives of metal nanopowders of different chemical composition. To evaluate damage to the material microstructure in the contact zone and its effect on the tribological characteristics of metal friction pairs, it is advisable to use a technique that determines the level of material damage based on the dispersion parameters of hardness values.
In general, the results obtained make it possible to conclude that lubricating compositions based on industrial lubricants saturated with additives of nanomaterials made of the friction pair’s component that has a lower hardness (in our case, these are steel K74 and steel 20) provide for a significant increase in wear resistance and ensure an acceptable friction coefficient. This confirms the possibility of using such lubricating compositions to enhance the wear resistance of the railway track elements (such as rails, turnout points, etc.).

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**References**

1. Uflyand, I.E.; Zhinzhilo, V.F.; Burlakova, V.E. Metal-containing nanomaterials as lubricants additives: State-of-the-art and future developments. *Friction* 2019, 7, 93–116. [CrossRef]

2. Elias, A.M.; Saravanakumar, M.P. A review on the classification, characterisation, synthesis of nanoparticles and their application. *IOP Conf. Ser. Mater. Sci. Eng.* 2017, 263, 032019. [CrossRef]

3. Zhenglin, T.; Shaohui, L. A review of recent developments of friction modifiers for liquid lubricants (2007–present). *Curr. Opin. Solid State Mater. Sci.* 2014, 18, 119–139.

4. Ivanov, S.P.; Afanasenko, V.G.; Boev, E.V.; Nikolaev, E.A. The Composition of the Metal-Containing Additive. RF Patent N 2355922, 18 June 2007. (In Russian).

5. Safonov, V.V.; Dobrinskiy, E.K.; Gorohovskiy, A.V.; Buylov, V.N.; Safonov, K.V.; Galkin, A.A. Lubricant Composition. RF Patent N 2525238, 9 April 2013. (In Russian).

6. Babel, V.G.; Garkunov, D.N.; Lapteva, V.G. Lubricant for Heavy-Duty Friction Units. RF Patent N 2338777, 1 August 2007. (In Russian).

7. Chausov, M.G.; Kosarchuk, V.V.; Pylypenko, A.P.; Tverdomed, V.M. A Method for Increasing the Wear Resistance of Friction Pairs Made of Metallic Materials. Ukraine Patent N 149049, 13 October 2021. (In Ukrainian).

8. Dai, W.; Lee, K.; Sinyukov, A.M.; Liang, H. Effects of vanadium oxide nanoparticles on friction and wear reduction. *J. Tribol.* 2017, 139, 061607. [CrossRef]

9. Padgurskas, J.; Rukuiza, R.; Prosyecevas, I.; Kreivaitis, R. Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles. *Tribol. Int.* 2013, 60, 224–232. [CrossRef]

10. Kosarchuk, V.; Chausov, M.; Pylypenko, A.; Tverdomed, V.; Maruschak, P.; Vasylikiv, V. Increasing Wear Resistance of Heavy-Loaded Friction Pairs by Nanoparticles in Conventional Lubricants: A Proof of Concept. *Lubricants* 2022, 10, 64. [CrossRef]

11. Tarasov, S.; Kolubaev, A.; Belyaev, S.; Lerner, M.; Tepper, F. Study of friction reduction by nanocopper additives to motor oil. *Wear* 2002, 252, 63–69. [CrossRef]

12. Abdullah, M.I.H.C.; Abdollah, M.F.B.; Amiruddin, H.; Tamaldin, N.; Nuri, N.R.M. Optimization of Tribological Performance of hBN/Al2O3 Nanoparticles as Engine Oil Additives. *Proc. Eng.* 2013, 68, 313–319. [CrossRef]

13. Singh, A.; Chauhan, P.; Mamatha, T. A review on tribological performance of lubricants with nanoparticles additives. *Mater. Today Proc.* 2020, 25, 586–591. [CrossRef]

14. Reshchikov, V.F. Friction and Wear of Heavily Loaded Gears; Mashinostroenie: Moscow, Russia, 1975; 232p. (In Russian)

15. Konicek, A.R.; Jacobs, P.W.; Webster, M.N.; Schilowitz, A.M. Role of tribofilms in wear protection. *Tribol. Int.* 2016, 94, 14–19. [CrossRef]
19. Luo, T.; Wei, X.; Huang, X.; Huang, L.; Yang, F. Tribological properties of Al₂O₃ nanoparticles as lubricating oil additives. *Ceram. Int.* **2014**, *40*, 7143–7149. [CrossRef]

20. Zhai, W.; Srikanth, N.; Kong, L.B.; Zhou, K. Carbon nanomaterials in tribology. *Carbon* **2017**, *119*, 150–171. [CrossRef]

21. Tao, X.; Jiasheng, Z.; Kang, X. The ball-bearing effect on diamond nps as an oil additive. *J. Phys. D Appl. Phys.* **1996**, *29*, 2932–2937. [CrossRef]

22. Tarasov, S.; Belyaev, S. Alloying contact zones by metallic nanopowders in sliding wear. *Wear* **2004**, *257*, 523–530. [CrossRef]

23. Ghaednia, H.; Jackson, R.L. The effect of nanoparticles on the real area of contact, friction and wear. *J. Tribol.* **2013**, *135*, 041603. [CrossRef]

24. Vakhрушев, A.V. Modeling of interaction nanoparticles with cracks on the surface of solids. *Procedia Struct. Integr.* **2020**, *26*, 256–262. [CrossRef]

25. AIMOL. Available online: www.aimol.nl (accessed on 28 August 2022).

26. Sergienko, R.A.; Ilkiv, B.I.; Petrovska, S.S.; Lopatko, K.G.; Lopatko, S.K.; Vinarchuk, K.V.; Hayasaka, Y.; Tomai, T.; Verkhovliuk, A.M.; Zaulychnyy, Y.V. Structure and properties of silicon nano and microparticles obtained by electric-spark dispersion method. *Mol. Cryst. Liq. Cryst.* **2022**, 1–16. [CrossRef]

27. Venger, R.; Tmenova, T.; Valensi, F.; Veklich, A.; Cressault, Y.; Boretskij, V. Detailed Investigation of the Electric Discharge Plasma between Copper Electrodes Immersed into Water. *Atoms* **2017**, *5*, 40. [CrossRef]

28. Veklich, A.; Lebid, A.; Tmenova, T.; Boretskij, V.; Cressault, Y.; Valensi, F.; Lopatko, K.; Aftandilyants, Y. Plasma assisted generation of micro- and nanoparticles. *Plasma Phys. Technol.* **2017**, *4*, 28–31. [CrossRef]

29. Lopatko, K.G.; Melnichuk, M.D.; Aftandilyants, Y.G.; Gonchar, E.N.; Boretskij, V.F.; Veklich, A.N.; Zakharchenko, S.N.; Tugay, T.I.; Tugay, A.V.; Trach, V.V. Obtaining of metallic nanoparticles by plasma-erosion electrical discharges in liquid mediums for biological application. *Ann. Wars. Univ. of Life Sci.—SGGW Agric.* **2013**, *61*, 105–115.

30. Hutchings, I.M. *Tribology: Friction and Wear of Engineering Materials*; CRC Press Inc.: Boca Raton, FL, USA, 1992; 273p.

31. Harris, W.J.; Ebersöhn, W.; Lundgren, J.; Tournay, H.; Zakharov, S. *Guidelines to Best Practices for Heavy Haul Railway Operations: Wheel and Rail Interface Issues*; International Heavy Haul Association: Virginia Beach, VA, USA, 2001.

32. DSTU 7793:2015; Metal Materials. Determination of the Level of Scattered Damage by LM-Hardness Method. ISO: Geneva, Switzerland, 2016; 15p. (In Ukrainian)

33. Myzuka, N.P.; Shvets, V.P.; Boiko, A.V. Procedure and instruments for the material damage assessment by the LM-hardness method on the in-service scratching of structure element surfaces. *Strength Mater.* **2020**, *52*, 432–439. [CrossRef]

34. Choi, Y.; Lee, C.; Hwang, Y.; Park, M.; Lee, J.; Choi, C.; Jung, M. Tribological behavior of copper nanoparticles as additives in oil. *Curr. Appl. Phys.* **2009**, *9*, e124–e127. [CrossRef]

35. Jatti, V.S.; Singh, T.P. Copper oxide nano-particles as friction-reduction and anti-wear additives in lubricating oil. *J. Mech. Sci. Technol.* **2015**, *29*, 793–798. [CrossRef]

36. Zhao, J.; Huang, Y.; He, Y.; Shi, Y. Nanolubricant additives: A review. *Friction* **2020**, *9*, 891–917. [CrossRef]