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IMPROVEMENT OF THE SERVICE LIFE OF MINING AND INDUSTRIAL EQUIPMENT BY USING FRICTION MODIFIERS

Purpose. Enhancement of the performance, service life and sustainability of industrial vehicles, mining machinery and various equipment by reducing the friction coefficient.

Methodology. Laboratory research on assessing the interaction of friction pairs under external loading, rolling, and sliding in dry friction conditions, as well as the influence of friction modifiers. Industrial experimental studies on the performance indicators of mining machinery under the influence of friction modifiers.

Findings. Actual diagrams depicting changes in the friction coefficient between the contacting surfaces of disc pairs were obtained for four specific loading periods and corresponding pressures of 529, 374, 274 and 187 MPa. These measurements were taken while the discs experienced a 10 % relative slippage and cyclic load interaction during the testing of specimens, with the presence of the repair-recovery compound called "Ideal" and without it, using only dry friction. The new technologies and the new repair-recovery compound "Ideal", developed at the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, provide an exceptionally low friction coefficient of 0.04–0.005 and ensure the durability of the protective layer under dry friction before failure, reaching 80–100 thousand cycles at a specific pressure of 529 MPa. At a specific pressure of 187–374 MPa, the protective layer under dry friction provides up to 1 million cycles of interaction.

Originality. The unique properties of the combination of the "Ideal" tribotechnical composition, which forms a metal-ceramic, superhard, refractory, and wear-resistant nanostructured layer on a metal base, have been established. This layer provides protection against wear, dynamic loads, thermal and oxidative degradation, and increases the service life of friction units in industrial equipment by 3–10 times.

Practical value. Based on the results of experimental and acceptance tests of the "Ideal" repair-recovery compound, a decrease in friction coefficient values and an extension of the service life of highly loaded gear mechanisms in mining and industrial equipment by 1.4–2.0 times have been established. It has been found that the protective layer provided by the "Ideal" repair-recovery compound helps reduce the wear mass of friction surfaces by 20 times in the tested samples, ensuring cleanliness of lubricants in equipment and increasing their operational lifespan while saving on maintenance costs.

Keywords: *friction modifiers, service life, friction coefficient, wear, industrial equipment*

Introduction. Equipment used in mining and industrial enterprises are among the most metal-intensive and energy-consuming sectors of the economy in Ukraine and the world.

In this regard, the development and implementation of resource-saving technologies aimed at increasing the service life of mining and industrial equipment is crucial. Particularly important is the conservation of lubricants and diesel fuel during the operation of technical means in industrial activities.

The relevance of this problem is primarily determined by significant operational costs associated with the maintenance and capital repairs of mining and industrial equipment, as well as technical means of various types of transportation and sectors of the economy. At the current stage of industrial development, the issue of excessive wear intensity of mechanical parts, industrial machine reducers, and the reduction of wear of contact surfaces in transportation systems becomes acute.

In addition, the improvement of the stability and durability of technical equipment provides the basis for enhancing safety in industrial, quarry and underground railway transportation.

Literature review. The analysis of the main research and publications aimed at improving the service life of mining and industrial equipment, as well as various types of transportation means with the development and implementation of resource-saving technologies, shows that the purposeful presentation of information is of great importance. It should be divided into components focusing on the service life, wear of contact surfaces, contamination of lubricating materials and the influence of friction modifier properties on the interaction processes of the components of technical equipment.

The analysis of the unsatisfactory condition of the main production assets of mining equipment is presented in the scientific work [1]. It is noted that over the last 20 years, the reconstruction and planned replacement of outdated stationary equipment in the coal industry have not been satisfactorily executed. Overall, the degree of wear of the main production assets in the coal industry exceeds 60 %. The use of outdated equipment leads to emergency conditions at the enterprise and significantly increases electricity consumption. The scientific work provides proposals for a strategy of rational management of mining equipment operation. However, the proposals do not address the issues of increasing the service life of technical means and their technical level.

The analysis of the unsatisfactory condition of the main production assets of mining equipment is presented in scientific work [1]. It is noted that over the last 20 years, the reconstruction and planned replacement of outdated stationary equipment have been insufficiently performed in the coal industry. Overall, the degree of wear and tear of the main production assets in the coal industry exceeds 60 %. The use of outdated equipment leads to emergency situations at the enterprises and significantly increases electricity costs. The scientific work provides proposals for a strategy of rational management of mining equipment operation. However, the proposals do not address the issues of increasing the resource of technical means and their technical level.

The issues of increasing the service life of industrial transport rail tracks by justifying the norms of their installation and maintenance, as well as studying the strength of rails under the influence of moving rolling stock under various rail support conditions, are covered in scientific works [2, 3]. However, these studies did not address the matter of enhancing the operational resource of industrial equipment through the properties of friction modifiers.

In scientific works [4, 5], research on increasing the productivity of mining rail transport and developing the mining industry in Ukraine by considering the braking characteristics of heavy articulated locomotives and braking devices for mine trains is presented. The studies cover the characteristics of friction and frictional contact vibrations during braking. However, these studies did not involve the use of systems to reduce the coefficients of friction between braking devices and the track structure.

The study [6] addressed the problems of the mechanics of friction processes in the wheel-rail contact zone with various coefficients of frictional coupling. Nonetheless, the scientific work did not address the issues of increasing the operational resource of mining equipment by reducing the coefficient of friction.

Theoretical and experimental research on the use of various braking devices in locomotives of mining rail transport is also presented in scientific works [6–8], where an assessment of wheel-rail contact conditions and adhesion is conducted using a multi-model approach. However, these studies did not explore the processes that influence the reduction of wear intensity on contact surfaces due to friction coefficient characteristics.

The service life of mining and industrial equipment, as well as transportation systems, is closely related to the wear process during the dynamic interaction of working components and technical elements.

The research conducted on the rail transport [9, 10] revealed that in curved sections with small radii of curvature ranging from 80 to 400 meters, the wear intensity of unprotected lateral surfaces of rails amounts from 10 mm to 4 mm per 1 million tons of gross passed cargo. Consequently, the service life of certain components of the rail track structure is 3–10 times smaller than the normative requirements, leading to an annual expenditure of over 1.1 billion UAH for their replacement and repair. The continued operation of such components poses safety risks and may lead to accidents.

Eliminating such drawbacks in operational conditions is possible by protecting the contacting surfaces from wear. These challenges can be addressed by significantly reducing the coefficient of friction between them.

One of the possible options to reduce wear is to coat the contacting surfaces with lubricant using spray nozzles and rail lubricators. Research [11, 12] has shown a positive impact on reducing wear intensity on the rail›s lateral surface by 2.5 times. However, drawbacks of such lubricants and technologies include a lack of adhesion, instability in maintaining the lubricant film on the metal surface, continuous contamination by sand and dust, and an unsatisfactorily high coefficient of friction, ranging from 0.1 to 0.15, instead of approaching zero.

The influence of friction coefficient values on the wear intensity of contacting lateral surfaces of rail heads and wheel treads of rolling stock and their relationship with the equipment and transport system›s operational lifespan is presented in publication [13]. It was found that reducing the friction coefficient from the range of 0.25–0.4 (under dry friction) to 0.04–0.005 (when using friction modifiers) results in a 3.5–4.5 times reduction in wear rates. The research findings demonstrate the direction of scientific exploration to address issues related to reducing wear intensity and increasing the operational lifespan of mining and industrial equipment by lowering friction coefficients in working mechanisms and processes. Modern scientific and technical achievements in nanomaterials and nanotechnology can be utilized to decrease friction coefficients and enhance the wear resistance of friction assemblies.

In scientific work [14], the method of multiple deposition of metal micro-particles on adjacent friction surfaces, transitioning to a quasi-liquid state of ultra-dispersed nanocrystalline metal layer, is discussed. The nanocrystalline amorphous metal has a clear boundary with the ultra-dispersed phase and contains a maximum amount of oxygen and carbon (up to 38 at. %) to create an oxide film in the surface layer. However, the method's drawback lies in its complexity for practical application and manufacturing processes, non-uniformity of the film structure on the metal surface, and its unsuitability for creating a protective layer for machines and mechanisms subjected to high loads and specific pressures.

The scientific work [15] discusses computer modeling of the process of forming functional nanocoatings using deposition methods from atomic fluxes of vapor or gaseous phases of substances. The research has theoretical and exploratory nature, which may be insufficient for practical application in scientific and technical tasks related to this study.

The research on the regularities of surface formation of nanoparticles under the influence of multifunctional oxide nanomaterials is presented in the work [16]. The interrelations of the modified nanoparticle surface state based on zirconium dioxide nanopowders are examined. However, a drawback of this method and the materials used is their insufficient durability under high levels of load and specific pressure.

The investigation of ceramic powder-based composites is carried out in the scientific work [17]. The created composites are used with metallic, ceramic, and polymer matrices. However, a drawback of such composite materials is their insufficient strength durability for metallic parts in an oily environment.

The enhancement of strength in nanosized crystals as they transition from three-dimensional to two-dimensional and one-dimensional crystals is examined in the scientific work [18]. The paper presents the results of theoretical and experimental studies of the boundary state of nanosized crystals under mechanical loading. The research has an exploratory nature with hypotheses regarding the strength enhancement at the level of carbon crystals.

The analysis of recent research and publications aimed at increasing the service life and efficiency of mining and industrial equipment, as well as various types of transportation systems, indicates an unsatisfactory state in terms of the reconstruction and planned replacement of outdated stationary equipment over the last 20 years.

The primary reason for the unsatisfactory state is the presence of intense wear on the contacting surfaces of working mechanisms, leading to a reduction in their service life by 3–10 times below the required standards.

The previously unsolved parts of the overall problem of increasing the service life of mining and industrial equipment include underestimating the influence of friction coefficient values on the wear intensity of equipment's working components, the creation of a wear-resistant layer with high strength to withstand significant cyclic and dynamic loads, as well as high specific pressure up to 10 % in the working parts of mining and industrial machinery and mechanisms.

The main directions of scientific research are focused on studying the impact of new friction modifiers to significantly reduce the coefficient of friction close to zero and their influence on reducing wear intensity and increasing the operational life of mining and industrial equipment.

The purpose of the study is to enhance the operational efficiency, lifespan, and stability of industrial transport, mining equipment, and various machinery through the reduction of the coefficient of friction.

To achieve the set purpose, the following research tasks are planned:

- evaluate the influence of friction coefficients between the contacting surfaces of interacting components in mining and industrial equipment on wear intensity indicators;
- conduct bench laboratory experiments to study the impact of different friction modifiers on the formation of friction coefficient values;
- perform experimental research to assess the effect of friction modifiers on the operational efficiency of mining and industrial equipment.

Methods. In connection with the above-mentioned main research directions, the following are assumed by the purpose and tasks of the work:

- conducting bench laboratory experiments to investigate the process of creating a protective layer on the contacting surfaces of mechanical components and studying the influence of the protective layer on the formation of friction coefficient values and equipment›s operational lifespan;

- carrying out operational research to assess the operational efficiency of mining equipment under the influence of friction modifiers.

The methodology for conducting bench laboratory experiments involves measuring the interaction parameters of friction pairs of test samples under external loads, rolling, and sliding in a state of dry friction. Additionally, it includes studying the influence of friction modifiers from repair-restorative compounds.

Fig. 1 depicts the samples used for bench experimental tests of the performance of repair-restorative compounds. These samples have a cylindrical circular shape with a central hole for mounting on the rotation axis. The manufacturing of the cylindrical test specimens is carried out with a temporary rupture resistance of not less than 900 MPa and a relative elongation of not less than 5 %.

The external cylindrical surface of the samples is subjected to microwave thermal treatment (microwave heating).

The contacting surfaces of the experimental cylinder samples are kept in a dry state to determine the coefficient of dry friction. Additionally, they are coated with various repair-restorative lubricant mixtures. In this setup, a calculated force is applied to the pair of contacting samples, causing them to wear during relative displacement with sliding friction.

During the tests, the following parameters are measured to assess the interaction between the friction pair of the experimental samples under external loading, rolling, and sliding: change in weight (mass) of the friction pair's experimental samples due to wear (in kilograms); change in diameters of the friction pair's experimental samples due to wear (in millimeters); determination of frictional forces (in Newtons) and, consequently, the coefficients of friction (dimensionless) between the experimental samples of the friction pair; determination of the hardness of the contacting surfaces of the experimental samples of the friction pair (measured in HRC units).

Fig. 2 shows the arrangement diagram of the experimental sample pair. The following parameters are indicated: *P* is converging force applied to the experimental samples during the tests; n_1, n_2 are rotational frequencies of the upper and lower experimental samples, respectively; D_1, D_2 are diameters of the upper and lower experimental samples, respectively; Q_1, Q_2 are weight of the upper and lower samples, respectively; HRC_1, HRC_2 are hardness of the surface of the upper and lower experimental samples, respectively; M_f is frictional force between the experimental samples; k_f is coefficient of friction between the experimental samples.

The benchtop experimental tests were conducted using the testing machine model SMU-2 (Fig. 3). The testing equipment underwent metrological certification.

All the components of the testing machine, equipment, and control systems are mounted on the frame *1* and the attachment *12*. The pivotable lever *2* provides controlled force loading between the test samples *3* and *4*. Sample *4* is fixed in the pressing fork on the swing lever *5*. The pressing fork is equipped with a screw *6*, which ensures the convergence and

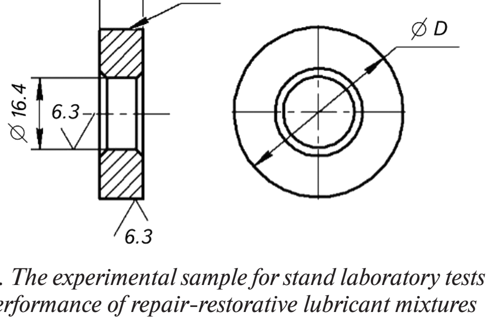

Fig. 1. The experimental sample for stand laboratory tests of the performance of repair-restorative lubricant mixtures

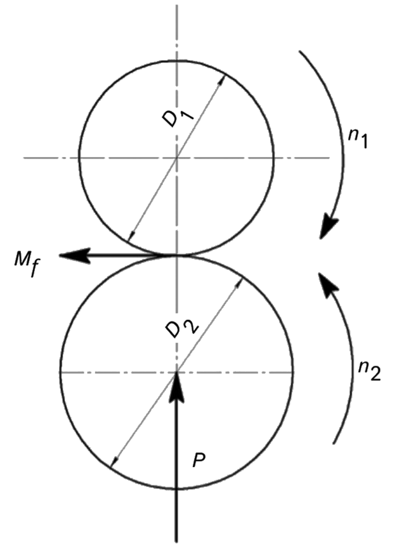

Fig. 2. Arrangement diagram of the experimental sample pair

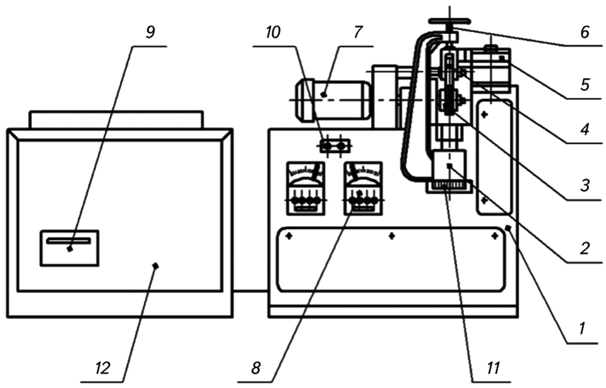

Fig. 3. Testing machine of the model SMU-2:

1 – frame; *2 – pivotable lever*; *3 – lower test sample* (*n* = 300 *rpm*); *4 – upper test sample* (*n* = 270 *rpm*); *5 – swing lever*; *6 – screw*; *7 – high-speed motor*; *8 – devices for measuring the rotation speed of the samples*; *9 – braking moment fixation device*; *10 – electric motor power buttons*; *11 – load scale for measuring the force between samples 3 and 4*; *12 – machine attachment*

the creation of compressive force (*P*) between the test samples *3* and *4*.

The speed reducer of the high-speed motor *7* is connected to a secondary reducer, which provides variable rotational speeds of the output shaft with the test specimen without coating. The speed difference between the test specimens *3* and *4* ensures the process of sliding friction on their contacting surfaces. The devices *8* display the rotational speeds of the test samples. The moment of traction (M_f) generated on the friction surfaces of the test samples *3* and *4*, and the load, are indicated by device *9* on attachment *12*. The force loading (*P*) of the test samples *3* and *4* is adjusted using the scale *11* and the dynamometer. For bench experimental tests, the force of specimen reduction (*P*) ranges from 0.05 to 1.00 kN (5–100 kg). The rotational speed of the upper test specimen was set at n_1 = 270,270 rpm, while the rotational speed of the lower test specimen was set at n_2 = 300 rpm. This ratio of rotational speeds n_1 and n_2 corresponds to a relative sliding of 10 %, equivalent to the relative sliding conditions on the lateral surfaces of the gear teeth in reducers of mining, industrial equipment, and other machinery.

The value of the friction force (P_f) between the test specimens and the coefficient of friction during the experiments is recorded on the chart of the strip chart recorder from the beginning to the end of the cyclic tests.

The required accuracy of measurements (characteristics) during the research is as follows: measurement accuracy of linear dimensions using a micrometer up to 10^{-6} m (0.001 %); weight measurement accuracy of the specimens at the beginning and during the experiments using analytical instruments up to 10^{-6} kg (0.001 %); Surface hardness determination accuracy of the specimens up to 0.001 %; friction force measurement accuracy up to 5 %; coefficient of friction determination accuracy during the research up to 5 %.

The processing of experimental data is carried out after completing each cycle of tests. The following parameters are determined:

- changes in the diameters of the test specimens (h_i)

$$h_i = D_i - D_{oi},$$

where D_i and D_{oi} are the diameters of the specimens before and after the tests, respectively;

- absolute value of the wear of the test specimens

$$\lambda_i = \frac{D_i - D_{oi}}{2};$$

- absolute value of the mass loss (m_i)

$$m_i = Q_i - Q_{oi},$$

where Q_i and Q_{oi} are the weight of the test specimen before and after the tests, respectively.

Results and discussion. The research on the influence of various lubricating compositions with friction geomodifiers has been conducted, and a new repair-recovery compound called "Ideal" has been developed. This compound is made from mineral raw materials and contains essential components such as SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, P_2O_5, K_2O, Na_2O, SO_3, ClO_2, ZnO, ZrO_2, along with fullerenes [19].

The study of the surfaces of the frictional pair of experimental discs (shown in Fig. 2) was carried out on a friction machine (shown in Fig. 3). The experiments were conducted with a relative sliding of 10 %. The first disc's rotational speed was $n_1 = 270$ rpm, and the second disc's rotational speed was $n_2 = 300$ rpm. The specific pressure was in the range of 187–529 MPa with a load of 0.1–0.8 kN (10–80 kg).

The study was conducted in four conditional periods with different modes:

- the first period involved dry friction of the test disc pair with a specific pressure of 529 MPa (under the load of 0.8 kN or 80 kg) without the addition of friction modifiers;
- the second period involved the interaction of the test disc pair with direct introduction of the friction modifier into the contact zone. The specific pressure between the disc surfaces was stepwise changed with values of 529, 374, 274 and 187 MPa. This period characterized the process of creating a protective metal-ceramic wear-resistant coating on the contacting surfaces of the test discs and in the metallic base;
- the third period was characterized by the absence of friction modifiers between the test discs after thorough cleaning with alcohol. A dry friction process was established between the disc pair with specific pressure stepwise changed with values of 187, 274, 374 and 529 MPa. This period allowed obtaining the actual friction coefficient values and the effective number of cycles of interaction between the test discs before the destruction of the protective coating;
- the fourth period reflected the critical state of the protective coating destruction at the maximum specific pressure between the test discs of 529 MPa, with a sequential increase in the friction coefficient from the values corresponding to the performance of the protective coating to the maximum values corresponding to dry friction between the exposed metal surfaces of the test disc pair.

Figs. 4 and 5 present informative real diagrams showing the variation of friction coefficient values between the contacting surfaces of the experimental discs during four specified loading periods and corresponding specific pressures in the range of 187–529 MPa with a relative sliding of 10 % between the discs under the influence of dry friction and the action of the repair and restorative compound in the first period. Fig. 4 shows the cyclic testing diagrams of the "Ideal" repair-recovery compound, while Fig. 5 displays the diagram of cyclic testing using the alternative friction modifier RST [19].

The analysis of the variations in friction coefficient values, presented in Fig. 4, using the "Ideal" repair-recovery compound reveals that during the first research period, over approximately 10,000 cycles of interaction, dry friction occurs between the experimental discs with a friction coefficient $f = 0.32$, and in some cases, the coefficient of dry friction reaches up to 0.47.

In the second research period, over approximately 75,000 cycles of interaction, with a specific pressure of 529 MPa and a relative sliding of 10 %, the process of treating the contacting surfaces of the experimental discs with the "Ideal" repair-recovery compound is carried out to create a protective metal-ceramic layer according to the technology developed by the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine under the copyright [19]. The friction coefficient values during this period range from 0.04 to 0.07, representing the main process of creating the protective layer using the "Ideal" compound under the influence of the specific pressure between the experimental specimens of 529 MPa.

In the third research period, over approximately 20,000 to 25,000 cycles of interaction and with a relative sliding of 10 %, the process initiated in the second testing period continues with the influence of the "Ideal" compound on the formation of the protective layer on the contacting surfaces of the experimental discs. During this period, the specific pressure between the disc pair is gradually reduced in a stepped manner, starting from 529 MPa (0.8 kN) and decreasing to 374 MPa (0.4 kN), then to 264 MPa (0.2 kN), and finally to 187 MPa (0.1 kN). As a result, the friction coefficient values decrease to the range of 0.025–0.006, partially influenced by the reduction in the applied load from 0.8 to 0.1 kN and, correspondingly, the specific pressure from 529 to 187 MPa.

In the fourth testing period, the process of dry friction occurs between the pair of experimental discs (after cleaning the discs from the mixture with alcohol). A notable characteristic of the obtained results is that during the initial stages of reducing the specific pressure and load between the discs (187 MPa (0.1 kN) and 264 MPa (0.2 kN)), the friction coefficients range from 0.006 to 0.008. At a specific pressure of 374 MPa (0.4 kN), the friction coefficient equals 0.015 to 0.02. Further increasing the specific pressure and load between the disc pair up to 529 MPa (0.8 kN) leads to an increase in the friction coefficient up to 0.06.

A distinctive feature of the fourth testing period is the possibility of conducting a comparative analysis of the operational performance and the quality of the impact of friction modifiers based on the criteria of the friction coefficient value and its service life in the critical state of dry friction before the destruction of the protective metal-ceramic layer. When using the "Ideal" repair-recovery compound, a friction coefficient in the range of 0.04–0.06 is obtained over 80,000–100,000 cycles of interaction between the disc pairs at a specific pressure and load of 529 MPa (0.8 kN). In other variants of the "Ideal" compound studies, the stability of the protective layer was observed up to approximately 200,000 cycles of load interaction between the experimental discs.

In further testing, as shown in Fig. 4, after providing 100,000 cycles of dry friction, the protective layer gradually degraded over 40,000 cycles of loading, and the friction coefficient increased from 0.06 to 0.37.

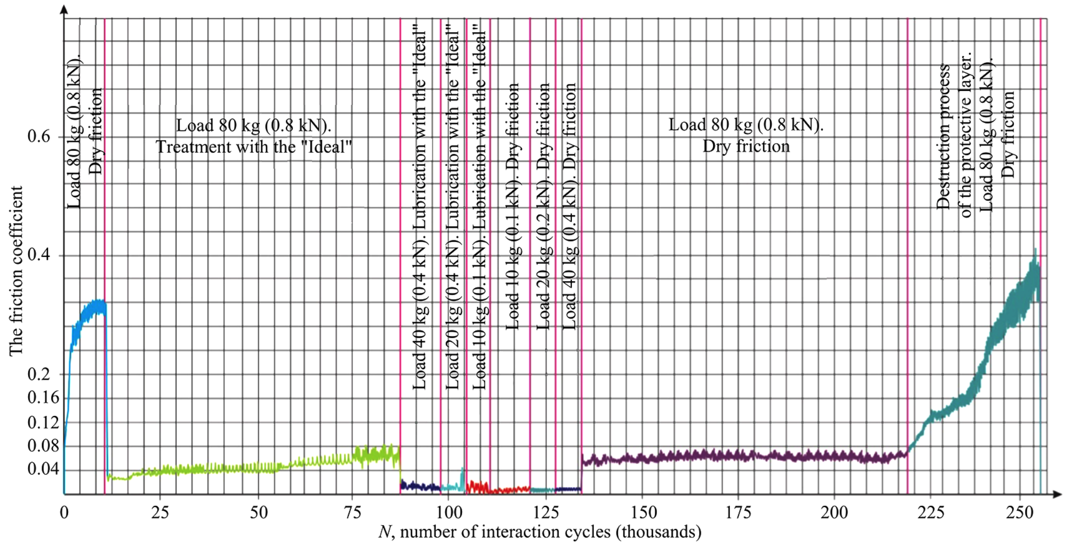

Fig. 4. Diagram of changes in the friction coefficient during the use of "Ideal" compound

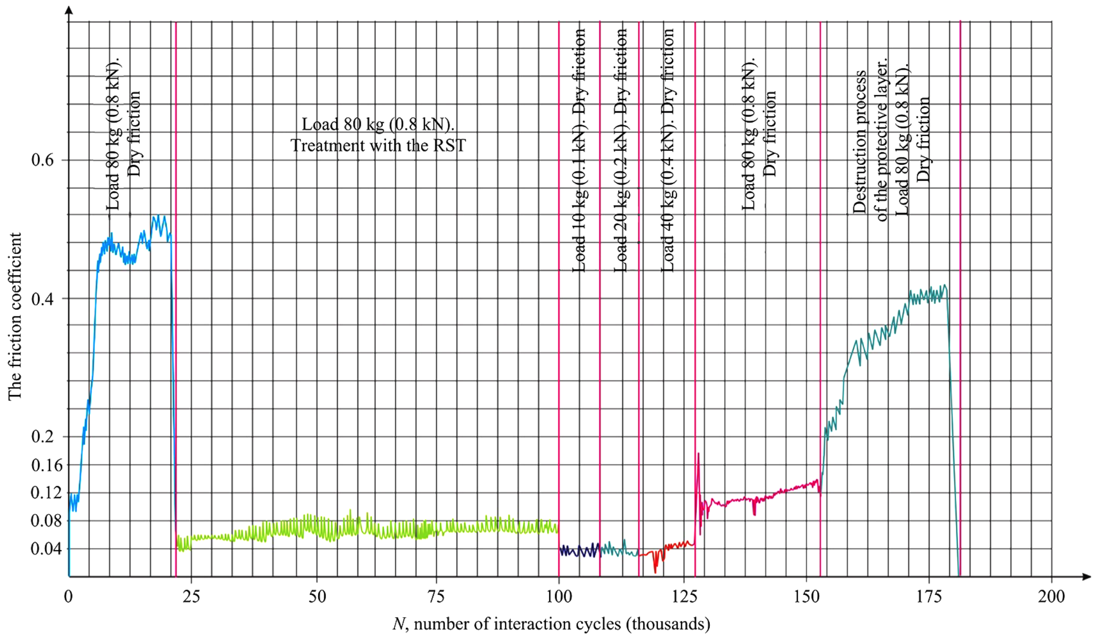

Fig. 5. Diagram of changes in the friction coefficient during the use of RST compound

During the conducted studies using the "Ideal" repair-recovery compound at specific pressures between the disc pairs of 187–374 MPa, the protective layer ensures friction coefficient values of approximately 0.004–0.005 for up to 1 million cycles of interaction. When the experimental disc pair operates in the working lubricant with the "Ideal" compound, at specific pressures of 187–374 MPa and a relative sliding of 10 %, the working life exceeds 200 million cycles of interaction with a friction coefficient of 0.004–0.006, maintaining the integrity of the protective layer for further use, and with no signs of wear on the contacting surfaces (further wear resistance tests were not conducted due to limited capabilities of the stand laboratory experiments).

The study results of the friction pair interaction process are summarized in the Table 1.

For comparison of properties and performance indicators, as well as friction coefficients of the "Ideal" repair-recovery compound with better alternative friction modifiers, the diagram of cyclic tests of the RST compound is presented in Fig. 5. The analysis of the main performance indicators of the friction modifiers shows that the friction coefficient after the creation of the protective layer with lubrication equals 0.08, and after the creation of the protective layer with dry friction and specific pressure between 187–374 MPa (0.1–0.4 kN), the friction coefficient is 0.04. Under the specific pressure of 529 MPa (0.8 kN), the friction coefficient ranges from 0.12 to 0.13. The durability of the protective layer before failure is 25,000 cycles.

The comparison of the main performance indicators of the "Ideal" and the better alternative RST compound shows that in the "Ideal" compound, the friction coefficient during dry friction is 6–7 times lower, and the wear resistance is 4 times higher.

The results of measurements of mechanical wear indicators of the test specimens at different stages of the research, including changes in diameter and weight of the specimens, are presented in Table 2.

The analysis of the test results of the mechanical wear indicators based on the criteria of reducing the diameter and weight of the test specimens using the "Ideal" compound, as shown in Table 2, indicates that the compound forms a protective layer with a thickness of up to 100 nm. This layer reduces

Table 1

The values of the friction coefficient variations for different variants and stages of testing, depending on the loading between the experimental disc pairs and the number of loading cycles

Lubrication Mode	Load, kN (kg)	Pressure, MPa	Friction Coefficient		Number of Loading Cycles, thousand cycles	
			per Spec.	Actual	per Spec.	Actual
Dry Friction	0.8 (80)	529	0.47	0.46	25.0	25.0
Friction with Systematic Lubrication	0.8 (80)	529	0.07	0.07	80.0	80.0
Friction with Systematic Lubrication	0.4 (40)	374	0.07	0.06	8.0	8.0
Friction with Systematic Lubrication	0.2 (20)	264	0.07	0.07	8.0	8.0
Friction with Systematic Lubrication	0.1 (10)	187	0.07	0.025	8.0	8.0
Dry Friction after Cleaning	0.1 (10)	187	0.01	0.006	8.0	8.0
Dry Friction after Cleaning	0.2 (20)	264	0.01	0.008	8.0	8.0
Dry Friction after Cleaning	0.4 (40)	374	0.03	0.02	8.0	8.0
Dry Friction after Cleaning without the Protective Layer Destruction	0.8 (80)	529	0.07	0.06	85.0	88.6
Dry Friction after Cleaning without the Protective Layer Destruction	0.8 (80)	529	0.04	0.37	25.0	27.0

Table 2

The averaged results of measurements of mechanical wear indicators for test samples

Indicators	Units	Values of indicators		
		During dry friction before treatment with the "Ideal"	During treatment with the "Ideal"	After treatment with the "Ideal" in dry friction conditions
Wear by sample diameter	mm	–0.018 (1.0)	–0.0128 (1.42 times reduction)	–0.00221 (8.23 times reduction)
Changes in sample mass	g	–0.0381 (1.0)	–0.0173 (2.2 times reduction)	–0.00191 (19.95 times reduction)

the mass loss by 20 times, which is separated from the friction surfaces. Additionally, it extends the service life of lubricants by 3–5 times.

This protective layer shields against dynamic, thermal, and oxidative degradation, leading to 3–10 times increase in the service life of friction components. It enhances thermal stability and keeps the oil cleaner by reducing wear weight significantly. Additionally, it ensures an exceptionally low coefficient of friction of 0.004–0.005.

These characteristics were obtained through extensive research on various combinations of tribotechnical materials and the "Ideal" repair-recovery compound, developed using new technologies [19].

The results of the conducted bench laboratory tests were utilized to establish the initial technical requirements for the development of the technical specifications TS U 20.5-13444170-001:2012 "Repair-Recovery Lubricant Compound "Ideal" for Mining Equipment" within the framework of UKND 75.100. Registered on 09.04.2012. Registration number: 0442941/10094,9 [20].

The experimental investigations of the performance of the "Ideal" repair-recovery lubricant compound were conducted in the gearboxes of electric drives of the 2LU 120 (No. 4) and 4L1200 (No. 5) belt conveyors along the Eastern Conveyor Mainline in the conditions of the Dovzhanska-Kapitalna Mine of SE Sverdlovantratsyt.

Based on the analysis of experimental research and acceptance tests, the following results were obtained:

- in the "IDLE" mode, the average power consumption of the 2LU 120 belt conveyor (with gearboxes treated with the "Ideal" compound) decreased by 2.1 % (2.2 kW);
- in the "LOAD" mode, the average power consumption of the 2LU 120 belt conveyor (with gearboxes treated with the "Ideal" compound) decreased by 8.7 % (13.5 kW), and the overall electricity consumption decreased by 9.7 % (180.5 kWh);
- in the control variant of the study under the identical operating conditions, without treating the gearboxes with the "Ideal" compound, the average power consumption of the 4L1200D belt conveyor increased by 14.6 % (16.3 kW), and the overall electricity consumption increased by 14.5 % (194.8 kWh);
- the adjusted sound power level of electric drives No. 1 and No. 2 of the 2LU 120 belt conveyor, treated with the "Ideal" compound, decreased by 3.4 % (2.3 dB) and 3.6 % (dB) respectively in the "LOAD" mode;
- vibration velocity on the high-speed shaft of electric drive No. 1 (in the *X, Y, Z* axes) decreased by 11.4, 43.2 and 46.7 % respectively;
- vibration velocity on the low-speed shaft of electric drive No. 1 (in the *X, Y, Z* axes) decreased by 41.4, 29.3 and 48.3 % respectively;
- vibration acceleration on the high-speed shaft of electric drive No. 1 (in the *X, Y, Z* axes) decreased by 1.9, 21.6 and 23.3 % respectively;
- vibration acceleration on the low-speed shaft of electric drive No. 1 (in the *X, Y, Z* axes) decreased by 10.3, 18.7 and 40.0 % respectively;
- the application of the technology and "Ideal" repair-recovery compound allows reducing the friction coefficient by 1.6–2.0 times and extending the service life of highly loaded gearboxes in mining equipment by 1.4–2.0 times through the creation of a protective metal-ceramic layer.

Conclusions.

1. The results of bench-scale experimental studies on the intensity and characteristics of wear of contacting surfaces of test specimens using dry friction and friction modifiers aim to increase the service life and operation stability of mining and industrial equipment and transportation means are presented.
2. The conducted studies focused on analyzing the properties of mineral raw materials found in the geological composition of land resources in Ukraine. The important components analyzed include SiO_2, Al_2O, TiO_2, CaO, MgO, P_2O_5, K_2O, Na_2O, SO_3, CeO_2, ZnO, ZzO_2 and fullerenes.
3. Real diagrams depicting the changes in friction coefficients between the contacting surfaces of test disks have been

obtained under characteristic four loading regimes with specific pressures of 529, 374, 274 and 187 MPa, at a relative sliding of 10 % between the disks, and cyclic interaction of loads between the test samples up to 1 million cycles for dry friction and up to 200 million cycles with the use of the "Ideal" repair-recovery compound.

4. The study has identified new properties of the tribotechnical composition of the "Ideal" compound, which create the superhard, refractory, and wear-resistant nanocrystalline layer on the contacting surfaces and in the metallic matrix. This layer provides protection against wear, dynamic loads, thermal, and oxidative destruction, and increases the service life of friction mechanisms by 3–10 times.

5. The new repair-recovery compound "Ideal" ensures the exceptionally low coefficient of friction, ranging from 0.04 to 0.005. The protective layer›s durability during dry friction reaches up to 80–100 thousand cycles at the specific pressure of 529 MPa, while at the specific pressure of 187–374 MPa, it can withstand up to 1 million cycles. When the test disks are operating in a working lubricant with the "Ideal" compound, the service life exceeds 200 million cycles, limited by the capabilities of the stand testing. These characteristics make the "Ideal" compound a highly effective solution for reducing friction and extending the service life of friction mechanisms.

6. The use of the "Ideal" repair-recovery compound helps reduce the wear surface mass by 20 times, ensuring the cleanliness of lubricants in equipment and increasing their operational life. This improvement in performance will lead to significant cost savings in equipment maintenance and operation, making it a highly beneficial solution for various industrial applications.

7. The research results have been utilized in the development of technical requirements, characteristics, and technical specifications TS U 20.5-13444170-001:2012 "Repair-Recovery Lubricant Compound "Ideal" for Mining Equipment" within the framework of UKND 75.100.

8. Experimental investigations and acceptance tests of the operational efficiency of mining industrial equipment under the influence of the "Ideal" repair-recovery compound were conducted on the gearboxes of electric drives for belt conveyors 2LU 120 and 4L 1200 in the conditions of the Dovzhanska-Kapitalna Mine of SE Sverdlovantratsyt.

9. Based on the results of experimental and acceptance tests, the application of the technology and the "Ideal" repair-recovery compound has shown the reduction in the coefficient of friction by 1.6–2.0 times and the extension of the service life of high-loaded gearboxes in mining and industrial equipment by 1.4–2.0 times through the creation of a protective metal-ceramic layer.

10. The comparison of the main performance indicators of the "Ideal" repair-recovery compound and the alternative RST compound reveals that in the "Ideal" compound, the coefficient of friction during dry friction is 6–7 times smaller, while the wear resistance is 4 times higher.

11. The research results are intended to be used for the development and implementation of new friction modifiers based on the properties of Ukraine›s mineral resources. These modifiers aim to increase the service life of industrial equipment, improve workplace safety in industrial enterprises, and significantly enhance the overall efficiency of industrial operations while reducing operational costs. Additionally, these advancements are expected to lead to substantial savings in material resources, including lubricants, which can extend the service life of various systems by 3–5 times.

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Підвищення ресурсу гірничого та промислового устаткування шляхом використання модифікаторів тертя

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Мета. Підвищення працездатності, ресурсу та стійкості роботи промислового транспорту, гірничого устаткування й різноманітного обладнання за рахунок зниження коефіцієнту тертя.

Методика. Лабораторні дослідження оцінки взаємодії пар тертя при зовнішньому навантаженні, коченні та проковзуванні у стані сухого тертя та впливу модифікаторів тертя. Промислові експериментальні дослідження показників працездатності гірничого устаткування під впливом модифікаторів тертя.

Результати. Одержані реальні діаграми зміни показників коефіцієнтів тертя між контактуючими поверхнями пари дисків за характерних чотирьох періодах навантажень і відповідному тиску 529, 374, 274 та 187 МПа при відносному проковзуванні між дисками 10 % і циклічній взаємодії навантажень між дослідними зразками з ремонтно-відновлювальною сумішшю «Ідеал» і за її відсутності з сухим тертям. Нові технології й нова ремонтно-відновлювальна суміш «Ідеал», що створені в ІГТМ НАН України, забезпечують особливо низький рівень коефіцієнта тертя, рівний 0,04–0,005, а стійкість роботи захисного шару при сухому терті до руйнування складає за питомого тиску 529 МПа 80–100 тис. циклів. За питомого тиску 187–374 МПа захисний шар при сухому терті забезпечує до 1 млн циклів взаємодії.

Наукова новизна. Встановлені особливі властивості сполучення триботехнічного складу суміші «Ідеал», що на металевій основі створює металокерамічний надтвердий тугоплавкий і зносостійкий наноструктурований шар, який захищає від зносу, динамічних навантажень, термічної та окислювальної деструкції та збільшує ресурс вузлів тертя промислового устаткування у 3–10 разів.

Практична значимість. За результатами експериментальних і приймальних випробувань ремонтно-відновлювальної суміші «Ідеал» встановлено зменшення показників коефіцієнту тертя і подовження ресурсу роботи механізмів високонавантажених редукторів гірничого та промислового устаткування в 1,4–2,0 рази. Встановлено, що при використанні ремонтно-відновлювальної суміші «Ідеал», захисний шар допомагає зменшити величину маси зносу поверхонь тертя дослідних зразків в 20 разів, що надійно забезпечує чистоту мастил в устаткуванні й обладнанні, збільшує ресурс їх роботи та економію експлуатаційних витрат.

Ключові слова: *модифікатори тертя, ресурс, коефіцієнт тертя, знос, промислове устаткування*

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