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USE OF THE SELECTIVE TRANSFER MECHANISM IN MOVABLE COUPLINGS USED IN POWER TRANSMISSIONS OF AGRICULTURAL MACHINES

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Abstract. Searching for new effective ways of increasing the wear resistance of power transmissions and improving their durability, the authors propose a device for enriching the lubrication system of power transmissions with copper-alloying elements. The tribochemical processes have been studied and the components of the lubricating composition have been selected to provide for the self-organized selective transfer in the "steel-steel" friction couples accompanied by the formation of a servovit film. The authors developed a utility model for enriching the lubricating system oil with copper-alloying elements for power transmission. For testing the effectiveness of the proposed additive and the method of forming the servovit film during operation, a roller test bench was used. It provided for synchronous measurement of the wear rate and the friction force moment during the whole experiment without disconnecting the friction zone. The friction zone (test contact) was formed by the cyclic surfaces of a roller with a diameter of 70.0 ± 0.1 mm made of steel 45 (HRs 50) and a homogenized pad with a radius of 35.0 ± 0.1 mm and dimensions (plan view) of 2.01 mm (along the sliding line) and 7.27 mm (across the sliding line). The friction area was 0.1461 cm^2. A set of normal forces: 730; 925; and 1130 N – was experimentally determined to ensure that there was no seizure. The shaft speed of 100 min^{-1} (a linear velocity of 0.37 m) was experimentally chosen under the condition of guaranteed absence of the hydrodynamic lubrication mode. The presented method of cladding additive production is easily implemented in the transmission units and also prevents the sedimentary instability of the lubricating composition. The device for enriching the lubricating system oil with copper alloying elements in the process of operation provides for a stable and self-organized mode of selective transfer. The results of tribological studies have shown the high efficiency of the cladding additive – the wear rate in the range of the normal force of 720 to 1130 N has reduced in 2.8…7 times.

Key words: power transmissions, wear, lubricants, lubrication mode, selective transfer, cladding additive, servovit film, surfactant, chelate complex.

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ОРИГИНАЛЬНАЯ СТАТЬЯ

РЕАЛИЗАЦИЯ МЕХАНИЗМА ИЗБИРАТЕЛЬНОГО ПЕРЕНОСА В ПОДВИЖНЫХ СОПРЯЖЕНИЯХ СИЛОВЫХ ПЕРЕДАЧ ПРИ ЭКСПЛУАТАЦИИ СЕЛЬСКОХОЗЯЙСТВЕННЫХ МАШИН

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Аннотация. В поиске новых эффективных путей повышения износостойкости силовых передач и повышения их долговечности предложено устройство для обогащения системы смазки силовых передач легирующими элементами меди. Исследованы трибохимические процессы и осуществлен подбор компонентов смазочной композиции, позволяющий реализовать самоорганизацию избирательного переноса в парах трения «Сталь-сталь» с образованием сервовитной пленки. Разработана полезная модель для обогащения масла системы смазки легирующими элементами меди силовой передачи. Для испытания эффективности предложенной присадки и способа формирования сервовитной пленки в процессе эксплуатации использовался роликовый испытательный стенд, предусматривающий синхронное измерение скорости изнашивания и момента сил трения в течение всего опыта без разъединения зоны трения. Зона трения (испытательный контакт) образована циклическими поверхностями ролика диаметром 70,0 ± 0,1 мм из стали 45 (HR_c 50) и колодки, прошедшей гомогенизацию, радиусом 35,0 ± 0,1 мм, и габаритами (в плане): 2,01 мм вдоль скольжения и 7,27 мм поперек скольжения. Площадь зоны трения составила 0,1461 см^2. Ряд нормальных сил: 730; 925; 1130 Н – определен экспериментально из условия гарантированного отсутствия признаков заедания. Частота вращения вала 100 мин$^{-1}$ (линейная скорость 0,37 м) выбиралась экспериментально из условия гарантированного отсутствия гидродинамического режима смазки. Представленный способ получения металлоплакирующей присадки легко реализуется в агрегатах трансмиссии, а также исключает седиментационную неустойчивость смазочной композиции. Устройство для обогащения масла системы смазки легирующими элементами меди в процессе эксплуатации обеспечивает устойчивый и самоорганизующийся режим избирательного переноса. Результаты трибологических исследований показали высокую эффективность металлоплакирующей присадки: интенсивность износа в диапазоне нормальной силы от 720 до 1130 Н снизилась в 2,8…7 раз.

Ключевые слова: силовые передачи, износ, смазочные материалы, режим смазки, избирательный перенос, металлоплакирующая присадка, сервовитная пленка, поверхностно-активное вещество, хелатный комплекс.

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Introduction. The analysis of automobile and tractor reliability shows that 20…40% of failures fall on the transmission units[1], the efficiency of which to a great extent depends on gears. Thus, during overhaul repair, over 60% of gears are discarded because of wear and fatigue failure [1-3].

The constructive and technological actions, aimed at increasing the wear resistance of gears, have largely exhausted their possibilities and do not provide a necessary resource [4]. In this connection, the search of new effective ways to solve this problem becomes extremely urgent. To solve this problem, it is necessary to use high-performance lubricants and consider lubrication conditions [5-7].

The discovery of selective transfer in friction (wear-free effect) made by researchers D.N. Garkunov and I.V. Kragelskiy (Priority No. 41, November 12, 1956), changed the prevailing view on the wear mechanism and developed a number of principally new materials and technologies [8, 9].

The research purpose was to increase durability of power transmissions through the implementation of the selective wear mechanism in the movable couplings of agricultural machinery.

Materials and methods. For surfactant synthesis, use was made of a heated magnetic stirrer and additional equipment. The assembled laboratory installation is shown in Figure 1.

Fig. 1. Laboratory installation for ligand synthesis

Рис. 1. Лабораторная установка для синтеза лиганда

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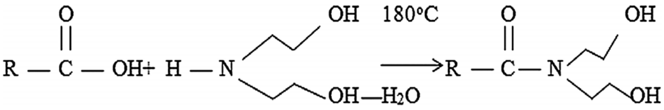
[1] Golubev I.G., Spitsyn I.A. Povyshenie dolgovechnosti detaley transmissiy sel'skokhozyaystvennoy tekhniki. Analiticheskie i obzornyye spravki [Improving the durability of farm machinery power transmission parts. Analytical and survey information]. Moscow, Informagrotekh, 1998. 5 p.

Technology of surfactant synthesis is as follows:

– pre-weighed reagents – one mole of oleic acid and two moles of diethanolamine – are loaded in a flask (0.5 l);

– this stage is followed by heating and stirring with a magnetic stirrer, the polycondensation reaction proceeds according to the following scheme:



The result is oleic acid amide with a product yield of 95%. The reaction time is three hours.

The implementation of the selective transfer mechanism in movable couplings of power transmission implies that a dipstick with the attached volumetric hollow copper profile is placed in the sump with the lubricating oil containing a surfactant as an additive (Fig. 2) [10].

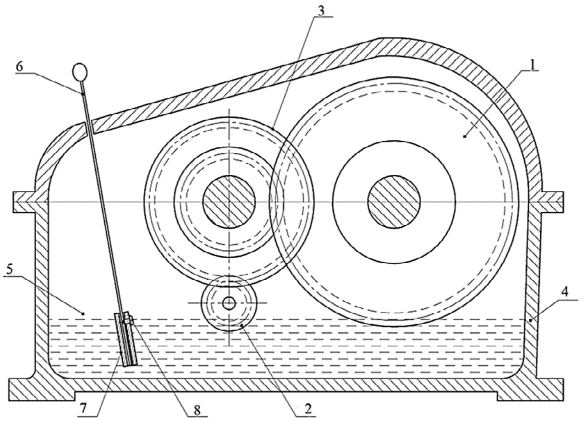
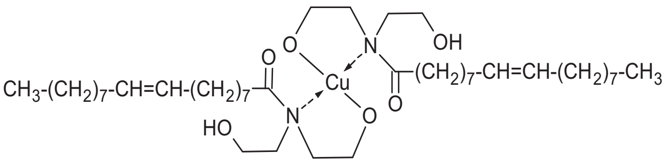


Fig. 2. Device for the implementation of selective transfer:
1, 2, 3 – pinions; 4 – oil sump; 5 – lubricating oil with surfactant; 6 – oil dipstick; 7 – hollow copper profile; 8 – fixing screw

Рис. 2. Устройство для реализации избирательного переноса:
1, 2, 3 – шестерни; 4 – поддон картера; 5 – смазочное масло с ПАВ; 6 – масляный щуп; 7 – объемный полый медный профиль; 8 – винт крепления

When the copper element comes into contact with the oil medium, an oleic acid diethanolamide-copper complex is formed, the structural formula of which is as follows:



The chelate complex turns green, indicating a copper-nitrogen chemical bond [11].

Results and discussion. To describe the formation of a protective copper film on friction surfaces, we should consider environment components, which can interact with copper or contribute to the formation of copper ions. We choose a plane-parallel model (Fig. 3) as a working area when a hydrodynamic component is absent in the transverse transfer of particles [12].

For making kinetic equations of mass transfer, we consider an interaction pattern of the system elements:

1. Surfactant molecules (B) interacting with the free surface of copper particles (H) adsorb on it to form surfactant coating ($H_{\text{в}}$)

$$\mathrm{H}+\mathrm{B}\overset{\text{к}_1}{\rightarrow}\mathrm{H}_{\text{в}}.$$

2. Oxidizing agent (C), reacting with the surface of copper particles (H), forms an oxide film ($H_{\text{с}}$)

$$\mathrm{H}+\mathrm{C}\overset{\text{к}_2}{\rightarrow}\mathrm{H}_{\text{с}}+\ldots\ .$$

3. The reducing agent (D) reacts with the oxidized surface and regenerates it:

$$\mathrm{D}+\mathrm{H}_{\text{с}}\overset{\text{к}_3}{\rightarrow}\mathrm{H}+\ldots\ .$$

4. As a result of surface unstrengthening (the Rebinder effect), the dispersion of $H_{\text{в}}$ and $H_{\text{с}}$ surfaces results in the emission of oxidized copper molecules (M) and copper ions (A) under the influence of the electric field [13]:

$$\mathrm{H}_{\text{в}}\overset{\tilde{k}_4}{\rightarrow}\mathrm{A}+\ldots; \qquad \mathrm{H}_{\text{с}}\overset{\tilde{k}_5}{\rightarrow}\mathrm{M}+\ldots\ .$$

5. Copper ions form oxidized copper molecules when interacting with the oxidizer:

$$\mathrm{A}+\mathrm{C}\overset{\text{к}_6}{\rightarrow}\mathrm{M}.$$

6. Oxidized copper molecules (M) react with a reducing agent and are reduced to copper ions:

$$\mathrm{M}+\mathrm{D}\overset{\text{к}_7}{\rightarrow}\mathrm{A},$$

where $\text{к}_1\ldots\text{к}_7$ are rate constants of the adsorption of a surfactant on copper, oxidation, reduction, yield of copper ions, yield of oxidized copper, oxidation and reduction of copper ions, respectively.

Note that the dimensionality of the rate constants is determined by the reaction form.

Denoting the concentration and area variables by appropriate small letters, taking into account diffusion, as well as the drift in the electric field (for charged copper ions), we obtain a system of differential equations:

$$\begin{cases}
\dfrac{\partial h}{\partial t}=k_1hb-k_2hc+k_3h_cd,\\
\dfrac{\partial h_B}{\partial t}=k_1hb-\overline{k_4}h_B,\\
\dfrac{\partial h_c}{\partial t}=k_2hc-k_3h_cd-\overline{k_5}h_c,\\
\dfrac{\partial b}{\partial t}=D_B\dfrac{\partial^2 B}{\partial x^2}-k_1hb,\\
\dfrac{\partial c}{\partial t}=D_C\dfrac{\partial^2 c}{\partial x^2}-k_2hc-k_6ac,\\
\dfrac{\partial d}{\partial t}=D_D\dfrac{\partial^2 d}{\partial x^2}-k_3h_cd-k_7md,\\
\dfrac{\partial m}{\partial t}=D_M\dfrac{\partial^2 m}{\partial x^2}+k_6ac-k_7md+\overline{k_5}h_c,\\
\dfrac{\partial a}{\partial t}=D_A\dfrac{\partial^2 a}{\partial x^2}-\dfrac{\partial}{\partial x}\eta E_xa+\overline{k_4}h_B+k_7md-k_6ac,
\end{cases} \qquad (1)$$

where D_n is the diffusion coefficient; η – is the mobility coefficient of copper ions; E_x is the projection of the electric field strength on the OX axis.

The form of the system equations (1) is determined by the law of the conservation of matter. For any n^th^ component

$$\frac{\partial n}{\partial t}=\frac{\partial j_n}{\partial x}+K_n,$$

where j_n and K_n are flux and reproduction of the component. re the flux is determined by diffusion and drift, and the reproduction by the interaction pattern.

The rate constants $\tilde{k}_4$ and $\tilde{k}_5$ are determined by the dispersion rate of the $H_в$ and $H_с$ surfaces, and hence depend on the surfactant concentration: the greater the value of B is, the more actively the dispersion process is going on.

In linear approximation

$$\tilde{k}_4=k_4B; \qquad \tilde{k}_5=k_5B.$$

The electric field strength as a function of coordinates in this problem is also unknown. Poisson's equation should be added to the system of equations (1) to determine it:

$$div\,E=\frac{\rho}{\varepsilon_o\varepsilon},$$

where ρ is electric charge density, Kl/m^3, ε_o is dielectric constant, $\varepsilon_o=0,885\cdot10^{-11}$ F/m; ε is the dielectric permittivity of medium.

Let us consider electrokinetic processes in the friction zone. The electric field arising in the friction zone is determined by two components: the field from the boundary surfaces and the field from the charges in the medium [14, 15]. To determine the electric field in the gap, we should first find the field from the boundaries (which corresponds to the solution of the problem at low charge concentrations in the friction zone) and then use this result to set the boundary conditions for solving the problem with an arbitrary charge concentration in the friction zone.

Friction under boundary lubrication is accompanied by surface electrical phenomena. One of them is the establishment of galvanic potential at the interface between metal and electrolyte, caused by the formation of an electric double layer at the interface [16]. Thus, the surface is piecewise polarized.

The potential created by such a surface [13],

$$\varphi=-\frac{v}{4\pi\varepsilon_o}\Omega,$$

where v is the momentum of the electric double layer; U is the space angle at which this surface can be seen from the observation point.

The copper cladding of moving parts of machines and mechanisms results from the thermal dissociation of copper complex on rubbing surfaces, the reduction of copper ions by electrons, coming from iron atoms contained by these parts, and the subsequent deposition of copper atoms on this surface leading to the servovit film formation. All of the above reactions occur with the surfactant – diethanolamide oleic acid, which is the main component of the additive. Acting as a ligand, it is coordinated by a divalent copper ion. An indication of a coordination bond formed between copper and nitrogen is the blue-green colouring of the lubricating mixture.

The tribological system operating in a steady-state selective transfer mode is a multi-component heterogeneous medium containing copper ions, surfactants, an oxidant, a reducing agent, oxidized copper, and copper particles (Fig. 3).

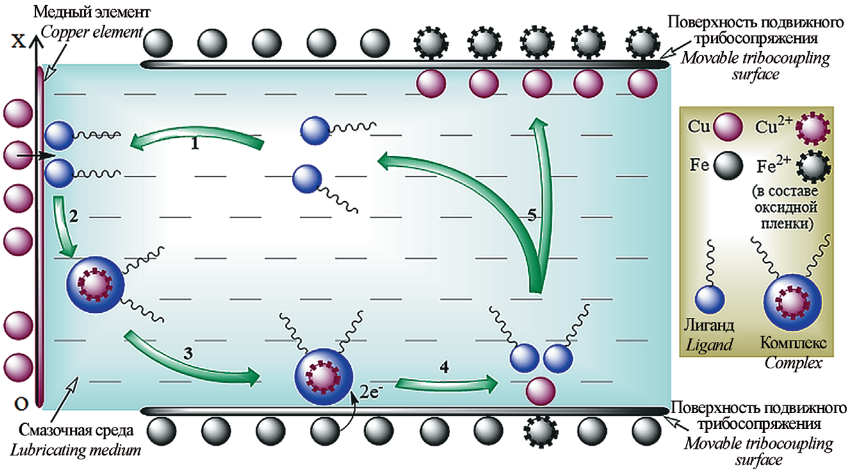


Fig. 3. Plane-parallel model of the friction zone in the steady state selective transfer mode:
1 – adsorption of ligand molecules on the copper surface; 2 – formation of the chelate complex of copper;
3 – adsorption of the chelate complex of copper on the tribocoupling surface;
4 – tribodegradation of the copper complex on the coupling surface and the reduction of copper ions;
5 – formation of the servovit film on the surfaces of the movable coupling

Рис. 3. Плоскопараллельная модель зоны трения в установившемся режиме избирательного переноса:
1 – адсорбция молекул лиганда на поверхность меди; 2 – образование хелатного комплекса меди;
3 – адсорбция хелатного комплекса меди на поверхность трибосопряжения;
4 – трибодеструкция комплекса меди на поверхности сопряжения и восстановление ионов меди;
5 – образование сервовитной пленки на поверхностях подвижного сопряжения

The servovit film is formed during the interaction of system elements according to the scheme shown in Fig. 3.

In the steady state mode of selective transfer restoration of the servovit film occurs due to copper-containing components, first of all, particles and copper ions. Both of them tend to move towards the surface, however, not every surface can accept them. There is an active surface that can accept copper-containing components. This includes, above all, friction areas with the disturbed servovit film. In a real friction coupling, the surface at any given time consists of active and passive areas. Thus, a zero flux of particles and copper ions corresponds to the distribution at the passive surface. The passive surface cannot be considered constant because during the friction process it can be destroyed, and active areas can form on it. The movement of copper-containing components does not start with a uniform distribution throughout the friction zone, but with an equilibrium distribution. This distribution differs from equilibrium distribution in that the copper-containing components are distributed in close proximity to the surface. Their increased content near the emerging active surface contributes to a rapid restoration of the servovit film.

The relative movement of the surfaces changes their condition. As a consequence of local destruction, certain areas of the surface can become active towards the copper-containing components.

When surfaces interact in friction couplings, it is necessary to consider the factors that produce active surfaces, adhesive fracture and the formation of an active base metal surface as a result of friction surface interaction. These factors include the surface finish and the operation mode of the friction coupling.

At low loads or relative surface speeds, the active surface area can only decrease due to its interaction with the surfactant and oxidant, so the flux of copper-containing particles is insignificant and, therefore, the selective transfer mode cannot be sustained. At high loads and relative surface velocities the active surface area tends to maximum and large quantities of copper-containing components are required for the surface recovery.

In this case, their flux can be reduced due to the screening of the boundary potentials. If copper-containing components are not introduced in large quantities, there will be nothing capable of restoring the whole active surface, and the selective transfer mode will become unstable again. Thus, the condition of the friction surfaces determines the stability of friction coupling operation in the selective transfer mode. Local disturbances are necessary to ensure the selective transfer mode, and these disturbances must be sufficient, as only in this case the servovit film repair mechanism is readily activated.

Thus, a decrease in the friction and wear intensity at the steady selective transfer mode is caused by the following factors:

– complex interaction of medium components;

– boundary conditions in the form of potentials of piecewise polarized surfaces;

– attraction forces of copper ions and particles to friction surfaces;

– concentration of copper-containing components in a boundary layer of friction surfaces;

– formation of an active surface of a sufficient area;

– interaction of the media components with the surface.

To assess the effectiveness of the cladding additive (CA), a test installation was used in the selective transfer mode, providing for synchronous measurement of the wear rate and friction torque during the whole experiment without disconnecting the friction zone.

Transmission oil and the cladding additive were used as the lubricant composition. The base gear oil was used as a control sample.

The friction zone (test contact) was formed by the cyclic surfaces of a roller with a diameter of 70.0 ± 0.1 mm made of steel 45 (HR_c 50) and a homogenized pad with a radius of 35.0 ± 0.1 mm and dimensions (plan view) of 2.01 mm (along the sliding line) and 7.27 mm (across the sliding line). The friction area was 0.1461 cm^2. A set of normal forces – 730; 925; 1130 N – was experimentally determined to ensure that there was no seizure.

The shaft frequency of 100 min^{-1} (linear speed – 0,37 m) was experimentally chosen from the condition of the guaranteed absence of the hydrodynamic mode of lubrication, i.e. to the left of the roller speed value corresponding to $M_{fr.min}$ on the experimental relationship of Stribek.

The experiment results are shown in Figures 4-5.

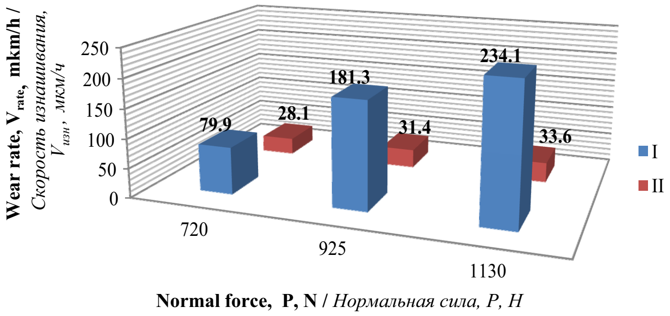
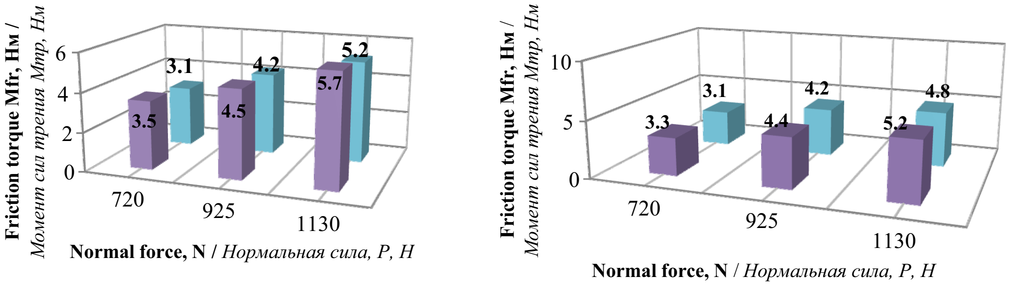


Fig. 4. Value of the pad wear rate as a function of the value of normal force at a temperature of the lubricating medium of 40°C:
I – control sample; II – tribocoupling with grease

Рис. 4. Значение скорости изнашивания колодки в зависимости от величины нормальной силы при температуре смазочной среды 40°C:
I – контрольный образец; II – трибосопряжение со смазкой



a b

Fig. 5. Relationship between the friction torque and the value of normal force:
I – tribocoupling with grease, II – control sample;
a – at a temperature of the lubricant medium of 40°C; b – at a temperature of the lubricant medium of 105°C

Рис. 5. Зависимость момента сил трения от величины нормальной силы:
I – трибосопряжение со смазкой; II – контрольный образец;
а – при температуре смазочной среды 40°C; б – при температуре смазочной среды 105°C

The control sample and the lubricant composition, as shown by the experiment results, demonstrated different interaction patterns between the rubbing surfaces of the roller and the pad. Cladding additives influence tribological processes in the boundary friction mode, therefore, wear reduction of friction pair surfaces is of the greatest interest. Of less interest is the reduction of friction torque, which influences the operating temperature of the lubricating oil in the friction unit. An increase in temperature can deteriorate physical and chemical indicators of lubricating oils during operation.

The experimental results showed that the cladding additive contributes to the reduction of wear intensity in the normal force range of 720…1130 N in 2.8…7 times, and the temperature of the lubricating medium has an insignificant influence. An increase in normal force slightly influences the lubricated tribocoupling wear rate as contrasted to the control sample (Fig. 4). For friction torque, the influence of temperature is insignificant for both the lubricant composition and the reference sample (Fig. 5). The lubricant composition shows a positive wear rate reduction effect when the temperature rises to 105°C, and wear does not intensify following the increasing normal load, which was not the case with the control sample.

Conclusions

1. The presented method of making the cladding additive can be easily implemented in the transmission units, and also prevents the sedimentary instability of the lubricating composition.

2. The method obtained has made it possible to design a device for enriching the lubricating system oil with copper-alloying elements during its operation and to ensure a stable and self-organized selective transfer mode.

3. The tribological study results have shown high efficiency of the cladding additive. The wear rate in the range of the normal force of 720 to 1130 N has decreased in 2.8…7 times.

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Contribution

M.N. Erokhin, S.M. Gaidar, A.F. Najim, A.Yu. Alipichev and A.M. Pikina performed theoretical studies and, based on the results obtained, conducted the experiment and wrote the manuscript. M.N. Erokhin, S.M. Gaidar, A.F. Naji Najm, A.Y. Alipichev, and A.M. Pikina have equal author's rights and bear equal responsibility for plagiarism.

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