Vol. 44, No. 1 (2022) 169-182, DOI: 10.24874/ti.1208.11.21.02

Tribology in Industry

www.tribology.rs

RESEARCH

Study on Frictional Properties of Fine Powder Materials

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Keywords:

Triboengineering
Friction
Wear
Oil
Additive

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Received: 1 November 2021
Revised: 27 December 2022
Accepted: 23 February 2022

ABSTRACT

The operating parameters of present-day engines depend on many factors, including the lubrication system. The lubrication system not only reduces friction between the surfaces of moving parts, but also contributes to their cooling and cleans engine parts from carbon deposits and impurities. High environmental requirements are also imposed on the quality of the lubricants, while maintaining their specifications. To that end, various additives are added to lubricating oil. The paper studies the effect of fine powders (enamels) on the wear of friction pairs in laboratory tests. The tests are mainly carried out for all-season synthetic and mineral oils in demand. Such criteria as wear of a roller and upper and lower bearings, specific wear of friction pairs, moment load, and temperature are selected as the effectiveness evaluation criteria of the use of enamels and nanomaterials. Experimental studies show a high efficiency of using enamels as additives to reduce friction and increase the load-carrying capacity of oils. The temperature in the friction layer is reduced by 10-20%, depending on the enamel concentration in the oil. The enamel acts as a third body with a lower friction coefficient and energy to failure, which increases the actual contact area of the friction pairs. The results of the study can be applied in the development of motor oils with fine enamel as an additive.

1. INTRODUCTION

The tightness of the combustion chambers is one of the main life characteristics of the engine performance. The cylinder-piston group (CPG) of the internal combustion engine (ICE) works in the most difficult conditions: gas environment, high temperature, and heavy repeated loads. This leads to significant wear of the piston rings and the cylinder liner, which entails a change in the ignition conditions in the piston space and has a great impact on the operation of engine systems. Due to the wear of the CPG, the compression is reduced and, accordingly, engine power decreases, the engine is hard to start, its oil and fuel consumption increases, and ultimately irreparable damage to the environment is caused. Over time, friction components of the engine and other aggregates of the vehicle, being subjected to the processes of natural wear, are destroyed, and various kinds of defects appear on them such as scratches, grooves, and other damage. In this case, expensive engine repairs are inevitable. However, with non-critical indicators of wear of its parts, there is an option for an in-place repair of the engine. The in-place repair technology is that when special additives are introduced into the oil in the friction units of the mechanism, the process opposite to wear occurs. In this case, a worn component or assembly is restored with the formation of coatings with significant wear resistance and a negligible coefficient of friction.

Effective lubrication of the relevant parts in a vehicle is necessary to provide their smooth sliding and reduce friction and wear in order to reduce the engine emissions and energy losses.

Since the first steam engines were invented, which used vegetable and animal fats to reduce the friction of moving parts, the evolution of the automotive industry has been tremendous, and with it, the related industries have developed such as lubricant oil manufacturing industry. The lubricating oil obtained from petroleum forms a thin film on the friction surfaces, which reduces the contact between them. The important characteristics of a lubricant are viscosity index, pour point, thermal stability, and oxidation resistance.

Depending on the origin and properties of the lubricating oils, they are divided into types [1,2]:

1. Mineral oils are obtained as a result of fractional distillation of crude oil. They are cost-effective, but not environmentally friendly, oxidize at high temperatures, and make the operation difficult at high and low temperatures.
2. Synthetic oils are obtained as a result of the synthesis in chemical plants. They are more stable to changes in external conditions and to oxidation. Such oil is more expensive than mineral oil, but without it, the operation of a vehicle at low temperatures is impossible.
3. Bio-lubricants include animal fats and vegetable oils and are an alternative to mineral oils. They have better lubricating properties, high viscosity index and high flash point and are environmentally friendly (biodegradable and extracted from renewable sources). The main classes of such oils are distinguished by the predominance of fatty acids: lauric acid (coconut oil), erucic acid (olive, rape, and mustard oils), ricinoleic acid (castor oil), and oleic and linoleic acid (palm, soy, earthnut, cotton, and sunflower oils).

Each type of oil has advantages and disadvantages, so research in the development of new types of oils has become widespread. It is possible to compensate for the shortcomings or improve some of the characteristics of the oil using special additives, which must have a number of physical and chemical properties:

- High solubility;
- Indelibility by water masses;
- Impossibility to settle on oil filters;
- Excellent oxidation stability performance of the oils;
- Prevention of part failures.

The main task of additives is to change the chemical structure of the oil in order to prevent certain effects in a vehicle motor system. There are several main types of oil additives [3-6]:

1. Anticorrosion additives form a special film on the metal surface of the parts, which helps to avoid the appearance of rust stains from the aggressive environment of the engine.
2. Antioxidant additives inhibit the oxidation reaction and prevent the catalytic effect of metal surfaces of parts.
3. Anti-foam additives act as a suppressant of a foam formation due to reducing the surface tension of the lubricant.
4. Friction modifiers help to avoid friction of mechanisms.
5. Polymer additives improve the performance of the viscosity-temperature balance of oils, which makes it possible to save fuel during vehicle operation.
6. Pour point depressants are additives that allow lubricants to flow at very low temperatures by reducing their pour points.
7. Dispersant additives protect the surface of mechanisms from foreign matter and keep

insoluble substances in the oil preventing them from precipitating.

8. Detergent additives contain surfactants that interact with various types of deposits (paint and varnish contamination, carbon deposits) and transfer them to a lubricating solution.
9. Anti-wear additives prevent strain aging of engine parts and their contact with each other.

The choice of the type of additives depends on the technical condition of the engine and operating conditions [7,8].

In order to improve performance and discover new properties of lubricants, it is necessary to constantly develop new environmentally friendly oils and improved additives [4-6,9-11]. Most of the lubricants produced do not have all the tribological properties.

The most important challenge currently is to develop lubricants that can be used even under harsh conditions and provide energy efficiency in various fields. This search for energy performance has led to current studies on the use of nanoparticles as lubricant additives. According to the history of the development of lubricant additives, nanoparticles are a relatively new class of additives to lubricant materials. It includes colloidal solid particles contained in lubricant oil [12-16]. The main components of nano oil materials are lubricant/basic oil, a nano oil additive, and a surfactant. Nano additives in a lubricant improve anti-wear and extreme-pressure properties and friction behavior. Surfactants are used to fill the interface between the lubricating oil and the nanoparticles. The use of nanoparticles as lubricant additives has some potential advantages [17]. The most important of them is the small size, which allows nanoparticles to penetrate into the contact zone. This contributes to the positive effect of lubrication. Other advantages are insolubility in non-polar base oils, low reactivity with other additives, and high possibility of film formation, which helps to withstand high temperatures and is more durable [18]. The effectiveness of nano additives depends on certain factors, such as their compatibility with base oils, their size and morphology, their concentration, and dispersion stability [19,20].

Many scientific organizations are currently investigating the tribological properties of oils and lubricating systems [1-5]. The compositions of additives to oils are continuously improved and their properties are enhanced [6-10]. Some studies are aimed at developing new environmentally friendly materials [11-14].

As a result of tests, Siti Afida et al. [11] found that palm oil-based lubricants easily decompose in an aqueous medium, in contrast to petroleum-based lubricants, and can be one of the alternatives to reduce the negative impact on the environment.

Sajeeb and Rajendrakumar [12] conducted studies with coconut and mustard oils, mixing them in different proportions. The authors see great prospects in the use of these ecological oils and plan to add nanoparticles to improve their properties.

Zainal et al. [15] argues that despite the advantages of biologically based lubricants, these lubricants are still far from being practical substitutes. Since biologically based lubricants are usually made from raw vegetable oils, these lubricants have poor cold flow properties, as well as low thermal oxidative and hydrolytic stability. However, these disadvantages can be eliminated by chemical modification of vegetable oils or the inclusion of additives in them.

Bio-lubricant researchers see a great future in the development of this type of lubricants and focus on their environmental safety as a priority in the development of modern tribology.

The direction of nanomaterials has received much recent development [16-21]. Nanostructured additives are used everywhere in mechanical engineering and vehicle operation. A large number of nanostructured powders are known, differing in the method of production, equipment used, and modes and conditions of production [22-26]. For example, the high efficiency of using additives with a size of less than 5 microns is proved, which contributes to the adsorption of oxides in power oil and the subsequent reduction in the part-wear rate [27-30]. The effect of reducing the electrostatic tension from the surface of parts and components is experimentally established [31-33]. Discrete additive particles are continuously present in the rubbing joints and contribute to intensive heat rejection [34-37]. Microparticles of additives introduced into the oil under the action of friction crumple and deform the surface microasperities and fill the cavities, activating processes on the friction surface [38-40]. Taking into account the ongoing processes, an increase in diffusion and chemical activity is observed in the friction zone.

In most studies, it is noted that the use of nanoparticles as additives to lubricants increases the lubricant operating performance. The optimal value of the concentration and the choice of nanoparticles in the lubricant depend on the specific functional requirements for the mechanism operation. The dispersion stability of nanoparticles must be maintained using surfactants, which requires additional costs for the development and manufacture of nano additives. The problem of environmentally safe use of these materials for humans and the environment is insufficiently studied.

In our study, we propose using powdered enamel with a relatively high hardness in the cold and a low melting point as an additive to engine oil (mineral and synthetic). It is assumed that enamel can act as an abrasive material that accelerates the alignment of mating parts, and under certain conditions of heating in friction contact, it can soften, turning into a plastic state, and be retained on the friction surface due to adhesion forces and molecular-chemical interaction with the metal. The effect of fine powder materials on the wear of friction pairs was studied in laboratory tests. For this purpose, the design of a device for measuring the friction torque was developed, on which the possibility of increasing and decreasing the friction torque and, accordingly, the wear of the pair depending on the process parameters was experimentally confirmed. The regularities and parameters of sliding friction in oil with the addition of fine powder materials were established.

2. MATERIALS AND METHODS

2.1 Selection of research material

When choosing powder materials, the main condition was satisfied: the powder material must have hardness and a melting point significantly lower than the base metal of the part. In this case, it could substantially lose hardness during friction, up to the viscous-liquid state under the action of heat generated by the friction of surfaces, filling the cavities of microasperities and gaps in the mating parts. In addition, this could allow for significant decrease in hardness before the transition to a viscous-liquid state and the effect of wetting the materials of the friction pair. Among the many materials that meet these requirements (for example, serpentine), basic enamel was chosen.

Enamel is an inorganic, opaque, low-melting glass of complex composition, intended for fusing onto metal in the form of a thin coating. The basis of the enamel is low-melting glass called in practice glass enamel. Glass enamel is deposited on the surface of metal parts and components to protect them against corrosion and various kinds of damage.

The complexity of the enamel compositions is due to the need to obtain such coatings from them that would have high adhesion to cast iron, steel or non-ferrous metals. There are ground and cover enamels. Ground enamels containing 50-60% SiO_2, 2–8% $A1_2O_3$, up to 30% B_2O_3, 12–30% Na_2O, 4–10% CaO, and other oxides (up to 10 names) are applied to the products with the first, ground layer, which adheres well to the metal. To strengthen the adhesion to the metal, so-called adhesion oxides Co_2O_3, Ni_2O_3, and MoO_3 are introduced.

We used serpentinite $Mg_6[Si_4O_{10}](OH)_8$ as an additive in the tests. Serpentinite has the following physical properties: compressive strength is 420–600 kg/cm^2, average hardness is 2.3–3.1, and density varies from 2.4 to 2.8 g/cm^3. During the experiment, the microhardness of the samples of friction bodies after testing was evaluated. The measurement was carried out using a PMT-3 micrometer [41]. The microhardness of the roller when providing a load of 100 g was 1840–1870 kg/mm^2. Practice of testing serpentinite-based additives shows that its use in a pure form gives high efficiency from 0.5 to 5 years of continuous use. The use of serpentine-based additives reduces wear during flat and surface friction by 2–13 times. Mechanical friction losses are reduced by 3–15%, the operation of mechanisms with internal and external gearing is improved, their operation noise is significantly reduced, and the efficiency of the internal combustion engine increases by 3–15%.

The use of serpentinite avoids physical wear, abrasion, surface embrittlement, electrochemical wear, and the restoration of worn mechanisms.

The high efficiency of serpentinite is provided by grinding to the micro level and dehydration. Under the influence of high pressures and temperatures in the ICE cylinders, noticeable changes occur in the surface layer of the cylinder metal. The result of its application is an increase in wear resistance by 1.2–5 times. A number of studies indicate the formation of a diamond-like carbon surface layer when introducing a serpentinite additive. It is the interaction at the carbon level that helps to reduce friction [42].

To compare the results of testing the enamel used, it is necessary to choose the nanomaterials.

Various nanomaterials have significantly different output parameters when tested. In [43], 10 nanomaterials passed the Timken test:

- FORUM friction modifier contains an ultrafine low-molecular-weight polymer polytetrafluoroethylene (PTFE), which has plastic and flow behavior under pressure;
- ARVO is mixtures of artificial or natural silicates of metals (ARVO is abbreviation for “antifriction and restoration of the overhaul period” in Russian). ARVO technology is based on the use of a specially developed ARV-composition, the addition of which to the lubricant allows restoring the shape and size and increases the resource of moving steel and cast iron units of any equipment without operation shutdown. ARV-composition is a suspension consisting of a base liquid and a complex mixture of artificial or natural metal silicates (which include serpentinites) in the form of a solid powder with particle sizes of 5-15 microns.
- RVD recovery reagent is anti-wear material, the action of which is based on the unique property of natural minerals of the layer silicate group (serpentinite, quartz, magnetite, etc.) to promote the formation of a durable antifriction composite carbon-containing diamond-like cellular structure on metal surfaces, that is, a modified surface layer strongly adhered to metal, affecting changes in the parameters of the tribosystem and the properties of its surfaces;
- FORSAN nanoceramics is manufactured on the basis of such a starting material as a layered hydrosilicate with a thin nanocrystalline structure, which contains a controlled fraction of active particles with a size of less than 100 nanometers. At the molecular level, FORSAN nanoceramics make a firm union with a metal, forming an ultra-hard protective metal-ceramic layer on it, that is, a metal-metal friction pair is replaced by a ceramic-ceramic friction pair;
- The RVS Master revitalizant is a geo-modifier of friction, based on such specific carbonaceous rocks as shungites and serpentinites. Shungite carbon has a high activity in redox reactions and, when heated, shungite rock begins to penetrate into the depth of the near-surface layer of the metal, causing its hardening. When the internal combustion engine is operating, high temperatures (up to 1000 °C or more) occur in micro-volumes in places of local contact, which leads to the initiation of micro-metallurgical processes such as micro-curing, micro-welding and charging. As a result, the particles of the RVS-master composition are “fused” to the crystal lattice of the surface layer of the metal. Thus, a monocrystalline glass-like structure is formed on the friction surfaces, optimizing gaps and wear;
- REAGENT-2000 is a complex consisting of specially prepared ultra-dispersed diamonds, organic compounds, metal catalysts, minerals and other components. Reagent 2000 differs substantially from most anti-wear compounds in that it protects the metal not only from friction, but also from hydrogen wear, which destroys the metal from the inside;
- SUPROTEC basically consists of balanced combinations of specially ground minerals of the layered silicate group (serpentines, chlorites, etc.). When used, the finely-powdered mineral composition initially actively cleans metal surfaces from deposits, carbon deposits, and only then forms a protective layer on the clean surface;
- WAGNER Micro Ceramic contains hexagonal boron nitride, the particles of which have an ultra-small size of 0.02–0.15 microns, as its main active component. Surfactants (components of the Eco-Universal additive) enter into a chemical compound with

molecules on metal surfaces and form a microscopically thin reaction layer (protective shield) that prevents welding of metal friction members. The consequence of this is a continuous and rather extensive leveling of surfaces. This leveling leads to the appearance of an exceptional, previously unattainable emergency galling resistance and a wear reduction;

- WAGNER Oil Package is a mixture of propylene glycol monobutyl ether, solvent, triphenyl-phosphorothioate, and amine phosphate as a liquid. It enters into a chemical combination with molecules on metal surfaces and forms a microscopically thin monomolecular protective layer that prevents wear of metal friction parts.

In the studies carried out, the maximum scuffing moment was controlled under equal test conditions (Figure 1).

Figure 1 shows that the smallest scuffing moment is observed when testing pure mineral oil. This indicates its low load-carrying capacity and somewhat large friction losses, with all other test conditions being equal, in comparison with other brands of nanomaterials. The best results were shown by samples from Wagner. Scuffing occurred at a moment equal to 100 N·m.

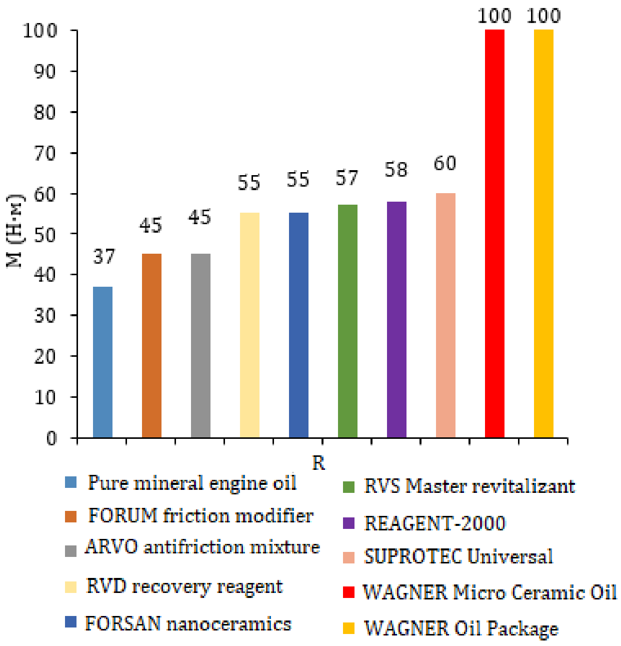

Fig. 1. Comparative bar diagram of the maximum scuffing moment control under equal test conditions depending on material brands (R).

2.2 Powder material preparation technique

When preparing the finest fraction of enamel powder, it is necessary to use wet grinding. To prevent dust formation and preserve finely ground particles, a small amount of non-polar liquid was added to the mass crushed into powder. In this case, it is impossible to use a polar liquid, for example, water, since its molecules envelop the particles of the powder to be ground, the destruction of the bonds of which in the future it will be necessary to expend energy. Isopropyl alcohol is used as a nonpolar liquid because it is nonvolatile. Vapors of this liquid mixed with air do not give a flammable or explosive mixture.

The initial criterion for powder readiness was the particle size of 0.2–0.4 mm. To separate the fractions of larger enamel particles, the crushed mixture was poured with alcohol, shaken, and stood for 1.5 minutes, 3 minutes, and 90 minutes. After that, the resulting liquid fraction with the smallest suspension of the powder obtained was merged. Then it was defended for three days and dried to the desired condition.

2.3 Theoretical calculation of wear parameters when testing a friction pair on the friction machine

To carry out a theoretical calculation of the wear parameters during tests on the SMC-2 friction machine, designed to test materials for wear and determine their frictional properties under conditions of sliding friction and rolling friction at normal temperatures, it was necessary to consider the following test conditions and set the measured and controlled parameters:

1. The friction pair load was 45 N;
2. Rollers made of 45 steel with a diameter of 50 mm, hardened to a hardness of 58HRC were used as friction pairs;
3. Templates cut from the crankshaft bearing of the D-180 engine were used as a counterbody;
4. The contact area with the counter sample was 100 mm^2. Before each test, the surface of the tribopair was sanded to create a certain (initial) roughness.

The surfaces of the rollers were previously processed by grinding and had different roughness values from *Ra*=0.0925…0.095 microns to *Ra* = 1.2 microns.

The roughness of the surfaces of the rollers and templates before and after the experiments was measured on the ABRIS PM7M profilograph-profilometer [44] with software for processing profilograms. The operation of the device is based on the principle of probing the surface under study with a diamond needle with a small radius of curvature and converting needle vibrations into voltage changes by the inductive method. After conducting the measurements with the ABRIS-PM7 profilograph-profilometer, a profilogram was taken.

After the control time, the force (*P*) at the end of the device lever and the temperature (*T*) in the contact zone of the counter sample with the lubricating medium were measured. Before and after the tests, the roller and bearings were weighed. Roller wear is calculated:

$$\Delta m_r = m_r - m_r^{'} \qquad (1)$$

where Δm_r is absolute wear of the roller; m_r is the roller mass before the test; m_r' is the roller mass after the test. Upper bearing wear is:

$$\Delta m_u = m_u - m_u^{'} \qquad (2)$$

where Δm_u is absolute wear of the upper bearing; m_u is the upper bearing mass before the test; m_u' is the upper bearing mass after the test. Lower bearing wear is

$$\Delta m_l = m_l - m_l^{'} \qquad (3)$$

where Δm_l is absolute wear of the lower bearing; m_l is the lower bearing mass before the test; m_l' is the lower bearing mass after the test.

Integrated specific wear of upper and lower bearings per operating hour of the friction pair is calculated:

$$U_{sp(u+l)} = \frac{60 \cdot (\Delta m_u + \Delta m_l)}{t} \qquad (4)$$

where *t* is testing time (min).

Specific wear of the roller per operating hour of the friction pair is:

$$U_{sp(r)} = \frac{60 \cdot \Delta m_r}{t} \qquad (5)$$

Total specific wear is:

$$U_{sp(total)} = U_{sp(u+l)} + U_{sp(r)} \qquad (6)$$

3. RESEARCH METHOD

The friction properties of fine powder materials were evaluated using the SMC-2 friction machine equipped with an additional device for determining the friction torque and with a partially modified scheme for loading the friction pair. Figure 2 shows the general scheme of the upgraded SMC-2 friction machine.

Fig. 2. General scheme of the upgraded SMC-2 friction machine.

Analysis of the SMC-2 friction machine operation showed a number of disadvantages, the most important of which was the measurement error. The existing drawbacks can be eliminated by proposing the design of the SMC-2 device for a friction pair disc-pad testing. Figure 3 shows a double friction pair.

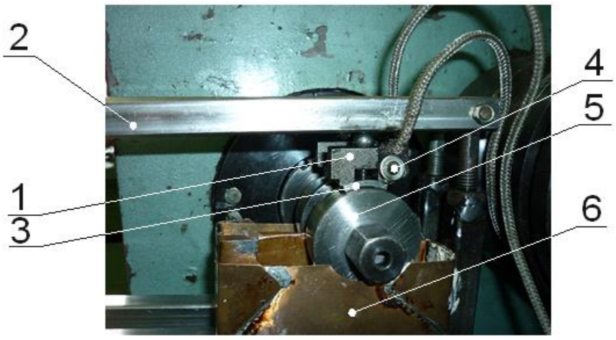

Fig. 3. The testing unit for double friction pairs: 1 – the pad screw retainment; 2 – the lever; 3 – the pad; 4 – the thermocouple-to-pad screw retainment; 5 – the rotating disc; 6 – the oil bath.

Two pads (3) are hung on the rotating disk (5) and fixed on the upper and lower lever (1), with the pad of the lower lever immersed in the oil bath (6). Thus, the lower friction pair is immersed in the lubricant, and the upper friction pair is lubricated with oil, carried out by the disc from the bath.

The loading of friction pairs is carried out according to a closed-loop power scheme and, unlike other designs, does not load the drive components with additional forces.

During the experiments, the force at the end of the lever of the device for measuring the friction torque was controlled using electronic scales, and the temperature in the zone of the counter sample contact with the lubricating medium was measured by switching the levers of the device. Temperature readings were measured with a chromel-copel thermocouple, which is most useful for measuring temperature under given conditions of the friction process.

The tests ended if two or three measurements of the friction torque were the same, that is, the running-in process was considered complete.

3.1 Temperature measurement technique

Temperature is the main parameter for friction and wear. According to its characteristics, a chromel-copel thermocouple of the second class is suitable for temperature measurement, since the expected temperature during measurement is 100°C ± 30°C. Therefore, a thermocouple with a measuring range from −40°C to 300°C is suitable.

Temperature can be an indirect parameter characterizing the operation of friction, since all types of energy are converted into heat: the higher the intensity of friction, the higher the temperature during operation. Heat is released at the counterbody friction boundary. The thermocouple is attached to the upper pad, since its lubrication and cooling conditions are worse in comparison with the lower pad placed directly in a bath with a lubricating medium.

Calibration was performed according to the readings of the device with the connected thermocouple when the junction of the thermocouple was in an environment with a pre-known temperature of the medium. Zero temperature was achieved with a mixture of ice and water, while one hundred degrees was obtained by boiling water. It was assumed that in the specified temperature range, the change in the EMF of the thermocouple is rectilinear.

4. RESULTS AND DISCUSSIONS

Before the main stage of the study, it was necessary to determine the magnitude of the loading force of the friction pairs. The criterion for choosing the load was the temperature of the friction pair. The temperature of the friction pair when working on pure oil should not exceed the values of 80...90°C set for most modern injection and diesel engines. This steady-state temperature was recorded when the friction pad was loaded with a force of 45 N. All experiments were carried out at the specified load of friction pairs and at the same speed of rotation of the roller (spindle of the SMC friction machine).

Figure 4 shows the experimental dependence of the oil friction moment (M_{fr}) on the test time.

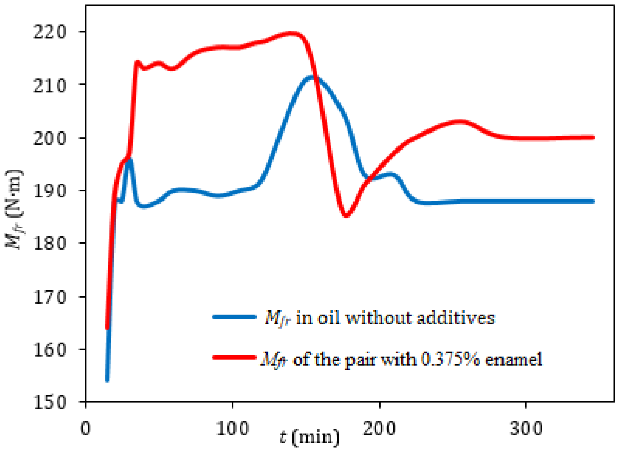

Fig. 4. The test time experimental dependence of the oil frictional moment.

At the initial step of loading (0–150 min), the friction torque of the pair with the enamel (0.375%) is much higher (Fig.4) than with oil without additives. The excess is on average 25 Nm. Further, with an increase in the test time, the difference of moments remains, but becomes less, about 11–12 Nm.

Figure 5 shows the experimental dependence of the oil friction pair temperature (T) on the test time.

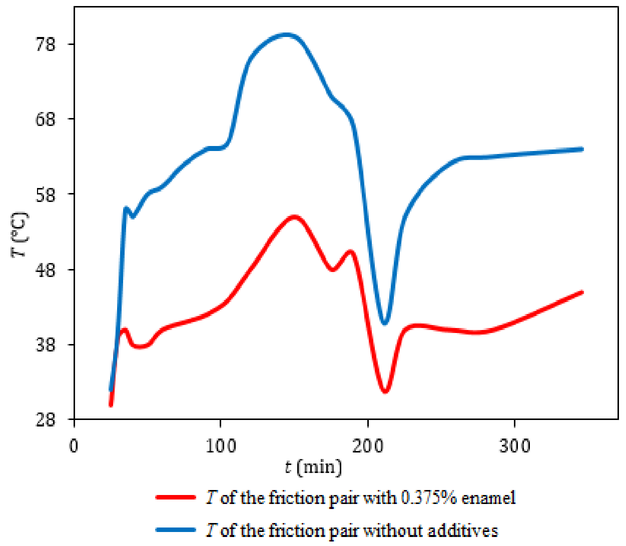

Fig. 5. The test time experimental dependence of the oil friction pair temperature.

Analysis of the data in Figure 5 shows that the addition of 0.375% enamel leads to a decrease in the friction pair temperature. This decrease averages 20°C.

The use of enamel as an additive in oil led to a decrease in the friction torque and the temperature of the friction pair under the same test conditions. However, tests of enamel additives of different concentrations have shown significantly different effectiveness.

The addition of an additive up to 0.375% led to a sharper change in the parameters of the friction torque and the temperature of the friction pair. An increase in the concentration of more than 0.375% led to a decrease in the effectiveness of the enamel. Thus, an additive of up to 0.5% was characterized by a minimal increase in efficiency. At a concentration of more than 0.5%, the effectiveness of the enamel was suspended and further testing of the friction unit led to the opposite result.

Figure 6 presents the experimental dependence of the oil friction torque on the test time. It shows that the friction moment decreases with an increase in the enamel concentration to 0.375%.

Figure 7 shows the experimental dependence of the oil friction pair temperature on the test time and we can see that the temperature of the friction pair decreases with increasing enamel concentration to 0.375%.

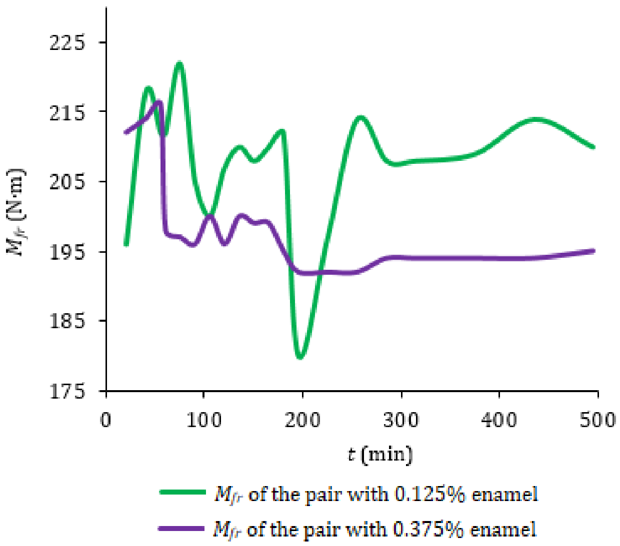

Fig. 6. The test time experimental dependence of the oil friction moment.

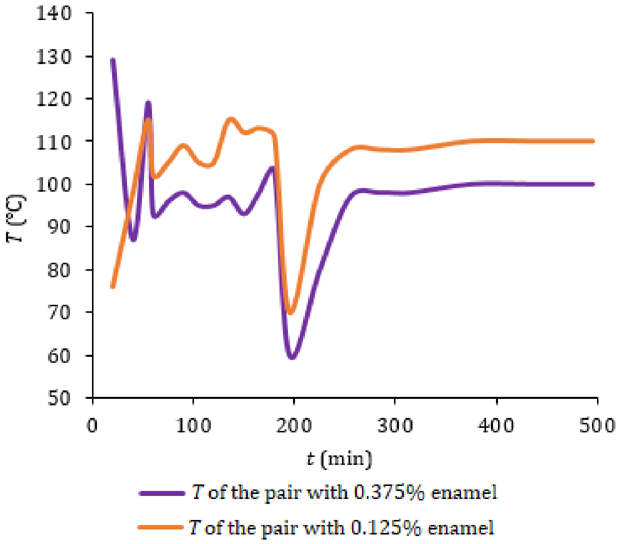

Fig. 7. The test time experimental dependence of the oil friction pair temperature.

In further experimental work, a comparative evaluation of the friction coefficients during operation of friction pairs under conditions with different concentrations of additives in synthetic and mineral oils was carried out. As a result of calculation according to experimental data, the dependence of the friction coefficient (*K*) on the test time was obtained when the friction pair was running on synthetic oil (Fig. 8).

The data presented in Fig. 8 indicate that the addition of enamel to synthetic oil leads to an increase in the friction coefficient. For example, a coarser fraction of the powder (3-minute) and its greater concentration leads to increased friction in comparison with a finer one (90-minute) and lower concentration.

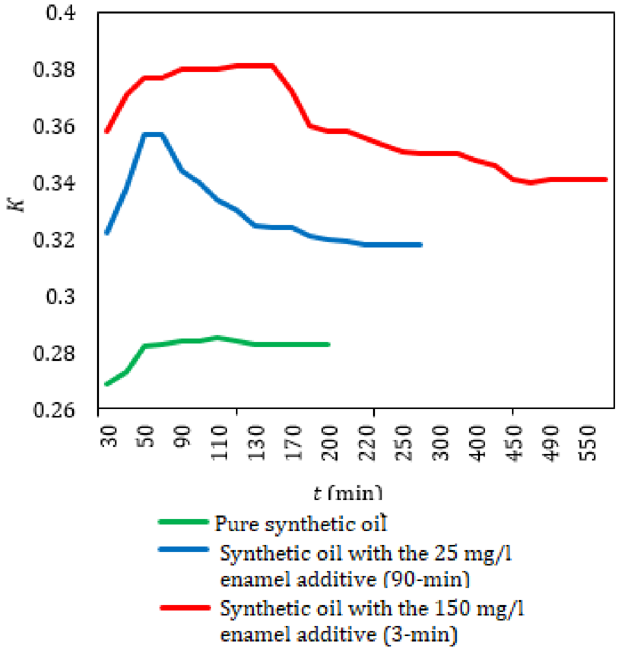

Fig. 8. The test time dependence of the friction coefficient for the friction pair operating on synthetic oil.

As a result of the calculation, the test time dependence of the friction coefficient was obtained for the friction pair operating on mineral oil (Fig. 9).

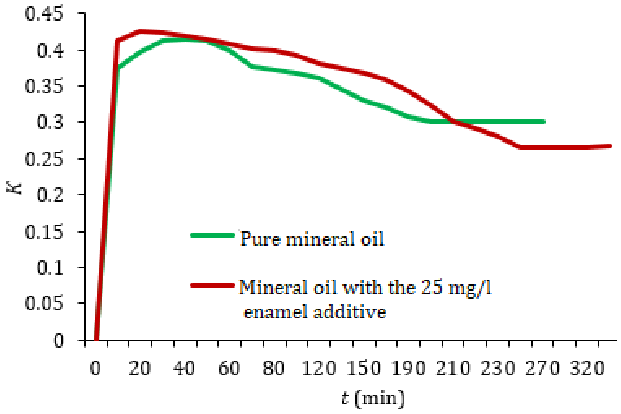

Fig. 9. The test time dependence of the friction coefficient for the friction pair operating on mineral oil.

As Fig. 9 shows, the coefficient of friction when using mineral oil is significantly higher than when using synthetic oil (Figs. 8 and 9). That is, the load-carrying capacity of synthetic oil is higher than that of mineral oil. But when a fine fraction (90-min) of powdered enamel is added to mineral oil, the coefficient of friction decreases at the end of the running-in stage. We can assume that the enamel in this case can act as a third body having a lower coefficient of friction and energy to failure and increasing the actual contact area of the friction pairs.

During the operation of friction pairs on synthetic oil with the addition of nanopowders (Fig. 10), the pattern of change in the friction coefficient is similar to the change in the friction coefficient for mineral oil (Fig. 9).

Figure 10 shows that the highest coefficient of friction is observed when testing Micro Ceramic in the range from 40 to 150 min. After that, the friction coefficient decreases and stays at the level of 0.234. For pure synthetic oil, the coefficient of friction at the beginning of the tests reaches the value of 0.263. Then it rises to 0.287 and at the end of running-in decreases and stabilizes at the level of 0.281. When testing the Oil-Package additive, the friction coefficient lies in the range of 0.182–0.20.

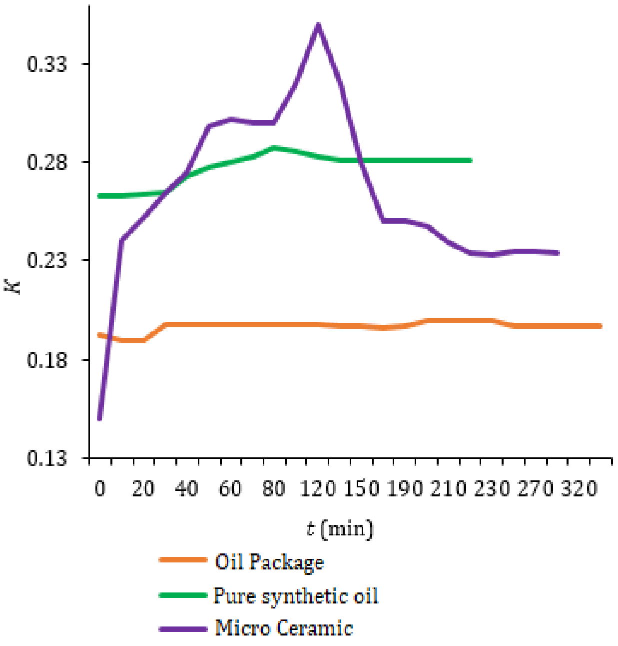

Fig. 10. The test time dependence of the friction coefficient for the friction pair operating on synthetic oil with nanopowder additives.

Comparing the data obtained during tests of pure oils and oils with the addition of fine powder materials, we found that these additives can reduce or increase the pair friction coefficient, depending on the granulometric composition of the powder and its concentration in the oil. But within the accepted duration of the test, the absolute values of the coefficient of friction with the addition of nanopowders are significantly lower than with powder enamel additives. Perhaps it depends on the average size of the enamel powder particles.

Studying the specific wear of the bearings (in total) (*U*) and the roller for 1 hour of operation on synthetic oil (Fig. 11), we can conclude that the larger the fine powder in its granulometric composition, the greater the wear of the friction pair.

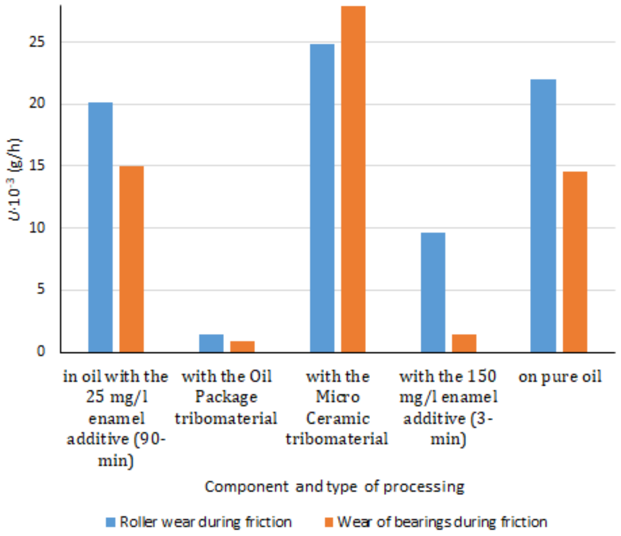

Fig. 11. Specific wear of friction pairs on synthetic oil.

According to Figure 11, the least wear of the roller and the bearing occurs during tests on synthetic oil with the Oil Package tribomaterial. The smallest wear of the bearing was also observed when testing synthetic oil with the 150 mg/l enamel (3-min).

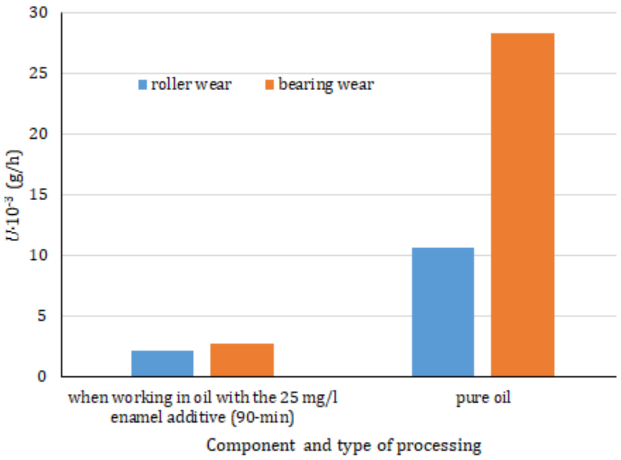

Fig. 12. Specific wear of friction pairs on mineral oil.

The data in Fig. 12 indicate that the specific wear of the friction pair with the addition of enamel was lower than with pure oil.

The difference in roller wear between two variants is $8.6 \cdot 10^{-3}$ g/h. The difference in bearing wear between two variants is $25.71 \cdot 10^{-3}$ g/h. It can be argued that under these test conditions, the specific load of the pair during friction on pure oil exceeded the load-carrying capacity of the oil (change to semi-dry friction mode), while the addition of enamel created the possibility of the formation of a steel-enamel friction pair. Thus, enamel being the third body, changed both the friction torque and wear of the pair.

5. CONCLUSIONS

In this paper, we studied the effectiveness of reducing the wear of parts when introducing various enamels and tribomaterials into the oil (Mobil Super 3000 5W–40 oil and SAE 10W–40 API SF/CC oil). Based on the tests carried out, we drew the following conclusions:

1. The friction moment of the pair with enamel (0.375%) was much higher than that on oil without additives, which led to a decrease in the temperature of the friction pair by an average of 20°C.
2. The addition of enamel to synthetic oil led to an increase in the friction coefficient: a coarse fraction of the powder (3-min) and its greater concentration led to an increase in friction compared to a finer fraction (90-min) and lower concentration.
3. The bearing capacity of synthetic oil was higher than that of mineral oil. But when a fine fraction (90-min) of powdered enamel was added to mineral oil, the coefficient of friction decreased at the end of the run-in stage. It can be assumed that the enamel in such a situation can act as a third body.
4. When working with friction pairs on synthetic oil with the addition of nanopowders, the pattern of change in the friction coefficient was similar to the change in the friction coefficient on mineral oil. When testing the Oil Package additive, the coefficient of friction lied in the range of 0.182–0.20.
5. When testing pure oils and oils with the addition of fine powder materials, the friction coefficient of the pairs decreased or increased depending on the granulometric composition of the powder and its concentration in the oil. Perhaps it depended on the average size of the enamel powder.

6. The least wear of the roller and the bearing occurred during tests on synthetic oil with the Oil Package tribomaterial. The least wear of the bearing was also observed when testing synthetic oil with the 150 mg/l enamel (3-min). The addition of enamel allowed for a steel–enamel friction pair formation. Thus, being the third body, enamel changed both the friction moment and the wear of the pair.

A technique for obtaining fine enamel powders was developed. A device design was proposed to increase the accuracy of measuring the friction moment. Laboratory tests confirmed the possibility of using fine enamel powders as an additive to mineral oil in order to reduce the friction torque in sliding bearings.

It can be recommended to conduct additional studies to clarify the concentration and granulometric composition of enamel powders, as well as the composition of enamel. The results of these studies will allow the use of fine powders based on enamel instead of the currently recommended expensive nanomaterials.

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