INTRODUCTION

The problem of significantly improving the reliability and life spans (resources) of internal combustion engines is highly important due to the tendencies of their power, purchasing costs, and costs of current and capital repairs to increase [1, 2]. The use of turbocharged uprated engines increased the requirements to the anti-friction, physicomechanical, and strength properties of friction surfaces. To increase the wear resistance of piston rings, porous chrome coatings are substituted with solid chrome and high carbon steel rings and tapes are installed in the zone of the highest wear of cast iron sleeves. In turn, the decrease in the oil absorption of solid chrome leads to burns and the fastening of rings with a sleeve mirror surface, which causes an increase in the capacity losses in a sleeve—piston ring friction pair, which are on the order of 10–12% engine power [3].

The search for ways to increase the durability of the working surface of sleeves at reinforced piston rings led to the need for targeted and consistent tribological treatments of ICE CPG by in-place methods in the process of nonstop operation. The reasonability of this approach is already undoubted.

The knowledge of wear rate (intensity) of machine elements enables one to determine the durability of the work of a friction pair. The wear rate of cylinder sleeves and piston rings depends on the mechanical stress state of rubbing bodies, the thickness of a lubricating layer, the physicochemical and electric surface processes, the presence of protective coatings, the temperature level, and other factors. It is difficult to obtain precise values of the wear intensity due to the instability of fields of stresses, deformations, and temperatures, the significant chemical impact of the environment, lubricant, fuel, combustion products, and abrasive particles. The examples of test calculations of average values of wear intensity of ICE sleeves showed that it lies in the range of $I_h = 10^{-9} – 10^{-11}$ [4, 5].

The aim of this work is to study the influence of the introduction of a geotribomodifier in the form of nanosized particles and then a metal placking agent in the ionic state into engine oil of a working engine.

MATERIALS AND METHODS

The tribological tests were performed using two friction machines, i.e., (a) 2070 SMT-1 according to the roller—block sliding scheme under boundary friction conditions, where a roller of $Ø50$ mm made of 40Kh steel ($HRC$ 48–50) was used as a movable sample and special cast iron for cylinder sleeves of D-240 engines manufactured at the Minsk Motor Plant (Republic of Belarus) was used as a block; (b) 77MT-1 with the reciprocating motion according to the sleeve—piston ring scheme (both elements made of special cast iron), the lower sample (a fragment of a sleeve) had a width of 20 mm and length of 100 mm, and the upper sample (a fragment of a piston ring) was processed on the outer diameter for a contact with a
sleeve at a length of 5 mm. The contact area of a ring with a sleeve was 10 mm².

Comparative tests were performed using the following lubricating materials:
1. M-10G2K oil;
2. M-10G2K oil with a geotribomodifier added into oil in a quantity of 0.15 wt %;
3. M-10G2K oil with an oil-soluble metal placking agent based on copper added in a quantity of 1.5 wt %.

The testing regimes using a 2070 SMT-1 friction machine were as follows:
— the rotational speed of a roller was 1000 min⁻¹;
— the sliding speed was 2.6 m/s;
— the load on the samples was 100–300 N;
— the lubrication method was drop lubrication with 20 drops of a lubricating material per minute;
— load on the samples was 80 N.

The profilograph tests were performed using a M-201 profilograph-profilometer (Kalibr plant).

MATHEMATICAL MODELING

Based on the use of physically informative invariants (complexes), an attempt was made to obtain a calculation equation for determining the wear intensity of ICE sleeves as a result of the tribochemical treatment, namely, the successive introduction of a geotribomodifier (GTM) and a metal placking agent (anti-friction) coatings on machine elements into the friction zone. Based on the contact-hydrodynamic theory of lubrication [6], a criterion was obtained that determines the thickness of a lubricating layer in the following form $h_{\text{lab}} / \sqrt{Ra_1^2 + Ra_2^2}$, the stress state is evaluated with a complex $fp_k / HB$. In addition, the surface roughness, which determines the carrying capacity of the contact, the oil absorption, and the oil-retaining ability, is characterized by a complex obtained by I.V. Kragel’skii and V.S. Kombalov $R_{\text{max}} / rb^{1/3}$. It is also necessary to introduce a complex of a $\tau_d / \tau_i$ type into the calculation equation that characterizes the ratio of the time of destruction of protective films of different origins to the time of their recovery.

Based on the Arrhenius–Zhurkov equation, the complex characterizing the physicochemical processes that occur on the friction surfaces and the destruction of boundary lubricating and modified surface layers of materials is determined; the criterion has the following form $RT/E$. For cylinder sleeves with cermet coatings, in the presence of anti-friction metal placking agents, it is necessary to include three dimensionless complexes [7, 8] that take into account the carrying capacity of cermet coated with a solid lubricant: $\Delta; \sigma_y/\nu; \tau_{\text{SH}}/K$, into the wear intensity equation. As a result, the equation has the following form:

$$J_h = k \left( \frac{Ra_1^2 + Ra_2^2}{h_{\text{bound}} + h_{\text{ch}}} \right)^{\frac{1}{2}} \left( \frac{fp_k}{HB} \right)^Y \left( \frac{R_{\text{max}}}{rb^{1/3}} \right)^Z \times \frac{\tau_d}{\tau_i} \left( \frac{RT}{E} \right)^Y \left( \Delta \right)^Y \left( \frac{\tau_{\text{SH}}}{\sigma_y} \right)^Y \left( \frac{\sigma_y}{K} \right)^Y.$$ 

By analyzing the obtained equation, it can be seen that, in order to decrease the wear intensity of cylinder sleeves, it is necessary to fulfill the following two conditions:

$$\left( \frac{fp_k}{HB} \right) \left( \frac{R_c}{tb^{1/3}} \right) \rightarrow \min \text{ and } \left( \Delta \right)^Y \left( \frac{\tau_d + \alpha p}{\sigma_y} \right) \rightarrow \min.$$ 

The first condition is related to the formation of a cermet coating with high hardness $HB$ and possibly low roughness of the bearing surface $R_c$ and coefficient of friction $f$ on the sleeve surfaces.

The second condition imposes the need to apply (presence) anti-friction coatings that have the lowest values of shear strength $\tau_0$, piezoelectric coefficient $\alpha$, and the optimal thickness $\Delta$.

RESULTS AND DISCUSSION

For the practical implementation of these conditions, technology that was developed for the complex consistent tribochemical treatment of ICE CPG has been proposed, which, at the first stage, forms a high modified cermet layer and, at the second stage, forms an anti-friction coating based on the composition of a metal placking additive. The obtained results of tribological (2070 SMT-1 friction machine, roller–block scheme) and microscopic studies (video analysis system), the changes in the moment of friction and the temperature in the contact zone (Fig. 1) and the microphotographs of the surface layer structures of cylinder sleeves (Fig. 2) show the presence of a significant reserve for the decrease in the friction horsepower (by 40–45%) of ICE CPG and the decrease in the heat release in the friction zone (by 35–38%) upon the targeted and consistent introduction of a geotribomodifier in the form of nanosized particles, followed by a