Improvement of Operational Parameters for High-Precision Tribosystems

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Abstract. In producing plunger pairs of high-pressure fuel pumps, product quality management has a problem of improving their durability and reliability. To improve the performance of products, it is advisable to pay special attention to the tribological characteristics of the friction surfaces that are part of such products, the conditions of their mutual contact, and lubrication. Using a scientific and experimental approach, friction pairs simulating the plunger pairs of high-pressure fuel pumps and aerial gases and diesel fuels used as working lubricants are investigated. The studies take into account the dual nature of friction. The obtained results do not contradict elastohydrodynamic and adhesion-deformation theories. A set of research equipment has been developed, demonstrating the occurrence of secondary currents in the contact zones and the effect of tribocavitation. In the process of friction, microbubbles dissolve in the diffuse contact region. It has been established that with certain types of microgeometric relief, contact load, and a temperature, it is possible to set precision surfaces, which may explain some types of failures of high-pressure fuel pumps and create conditions for expanding the temperature range of these products.

Keywords: Industrial growth · Contact pressure · Friction pair · Lubricating medium · Operational properties · Precision tribosurfaces

1 Introduction

Modern production tends to increase product durability, performance, and other operational and technological parameters [1]. Simultaneously, a change in the serial production may occur, and conditions for its rapid changeover to new types of products may be created, but the problem of controlling the accuracy and quality of production remains relevant [2].

Solutions to this and similar problems are inextricably linked to an increase in the production culture, a decrease in energy consumption, and the level of CO_2 emissions both at the production stage and during the operation of precision products [3]. An essential role in improving the performance of products is played by the methodological

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approach and the use of a laboratory and methodological base, which, together with modern software and control systems, makes it possible to obtain and analyze the main tribotechnical characteristics of the studied friction pairs in real-time with the necessary accuracy and reliability to improve their operational performance characteristics [4, 5].

Simultaneously, the study of tribocontact parameters, contact pressures, and lubrication regimes are priority tasks, the solution of which is devoted to a number of theoretical and practical works in modern tribology [6, 7].

2 Literature Review

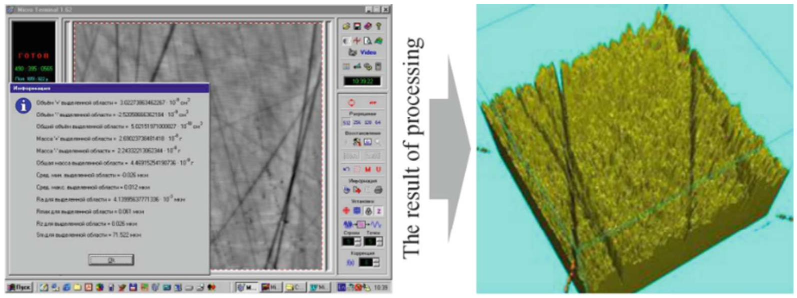
It is well known that 70…80% of wear of parts of friction units of ground and aircraft engines occurs at the time of their launch [8, 9]. From the standpoint of the adhesive-hydrodynamic model of friction and wear, this is explained by the fact that all friction nodes (from the moment of their movement to the exit to normal operation) pass areas of low speeds, if the limit friction mode is implemented [10, 11]. Under such conditions, the adhesive interaction and wear of the friction surfaces occur. Given the dual nature of friction, the mechanism of contact interaction in relative contact of friction surfaces should take into account physical models of surface phenomena [12, 13], microrelief of friction surfaces, depending on the type of mechanical and strengthening treatment [14, 15] and properties of lubricants and media. When developing precision tribosystems, new theories and approaches to friction and lubrication should be developed, models should be created and experimental studies of contact interaction should be conducted [16, 17]. Equally important is the position of increasing the reliability and durability of machines through friction modifiers, ensuring the operation of tribosystems, as well as the use of traditional and alternative fuels and lubricants and their impact on tribotechnical performance [18, 19].

There is a large amount of theoretical and experimental work in surface engineering, contact interaction of precision friction pairs, contact hydrodynamics, tribology of boundary lubrication [20]. However, almost no practical work combines the results of modern tribological achievements and technologies for the manufacture and assembly of high-precision products [21] to ensure elevated quality and management [22].

3 Research Methodology

The object of the study was plunger pairs, which are part of high-pressure fuel pumps (HPFP). Usually, the finishing operations for cleaning precision surfaces should be grinding operations with diamond pastes to the required clearance, which does not always provide the required surface accuracy and the ability to control the clearance [23, 24]. Therefore, a number of studies were conducted on precision polished tribo-surfaces in the mode of limiting friction on the developed laboratory research and testing equipment. Aviation gasoline TC-1 and diesel fuels of various supply series were used as lubricants [25].

The studied surfaces were treated with diamond pastes, by stepwise grinding with pastes of different grain sizes, to the required roughness (Fig. 1), which was monitored on a laser differential phase microscope profilometer (LDPMP) [26].



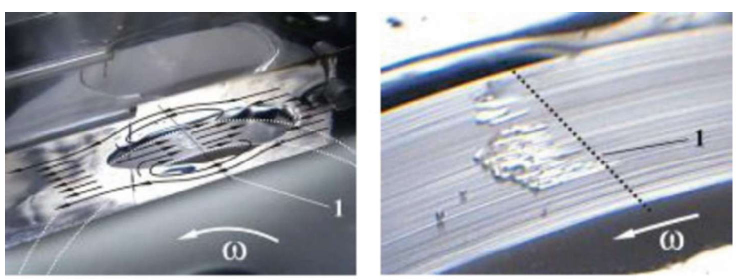
a) b)

Fig. 1. General view of the studied surface a) and microrelief b) of the studied surfaces on LDPMP.

High-pressure fuel pumps operate in different climatic zones at different temperatures, so an important scientific and practical task is to study the dynamics of boundary layers [27] under lubrication with different lubricants and ensure their trouble-free operation in a wide range of temperatures [28, 29].

Under operating conditions, it is stated that PHFP must operate in the temperature range from +40 °C to –30 °C. Very often, at temperatures below –20 °C, such pumps already fail due to the properties and quality of fuel the quality of the surfaces of the plunger pairs, and the gaps between them [30].

To study the dynamics of the boundary layers, a model friction pair was used: 100Cr6 steel - quartz glass. This allowed us to visually observe and investigate the occurrence of secondary flow in the contact zone (Fig. 2, a) and the effect of tribocavitation (Fig. 2, b) in the aviation medium at the speed of the model shaft (counter sample) ω [26, 31].



a) b)

Fig. 2. Visual studies of the model friction pair 100Cr6 steel - quartz glass in the environment of aviation gas: a) the occurrence of secondary flow in the contact zone; b) the effect of tribocavitation.

In addition, phase transitions were studied on the model friction pair at the rotational shaft frequency ω [32], particularly, all stages of nucleation, formation, and growth of gas-air mixture in dynamic equilibrium, tribocavitation process (as a partial case of cavitation), as well as partial dissolution of microbubbles in the diffuse (expanding) contact area [4, 25], Fig. 3.

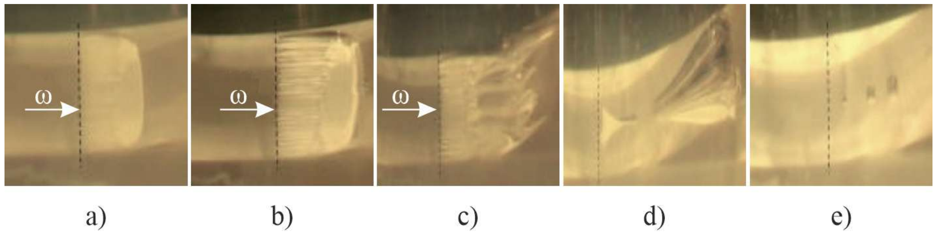


Fig. 3. Stages of formation of gas cavities at rarefaction of boundary layers in the diffuse region of tribocontact: a) nucleation at the initial moment of friction; b) growth and dynamic equilibrium with increasing speed; c) the emergence of cavitation processes; d, e) partial dissolution of gas cavities after cessation of friction.

In the framework of elastohydrodynamic friction theory, the calculated contact stresses that occur during surface compression are identified with the pressures in the boundary layers during friction [33].

That is, the pressure in the lubricating layer of the elastohydrodynamic contact is always higher than atmospheric pressure. Proponents of the adhesion-deformation approach hold the same opinion, where dynamic processes in the boundary layers are neglected [5, 34]. However, it is essential to investigate and experimentally measure the actual local pressures in the lubricating layers of the tribocontact during friction in the dynamics. The measurement results were recorded using an original computer program (Fig. 4).

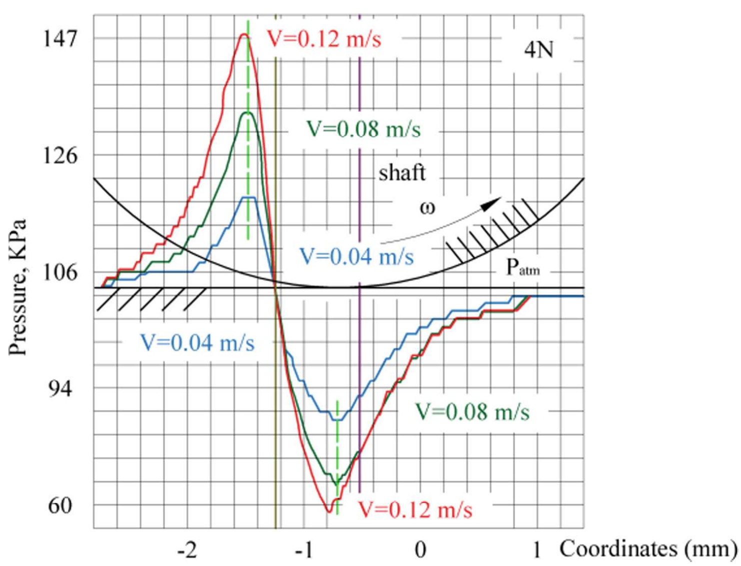


Fig. 4. The curve of the distribution of contact pressures of a series of experiments at a sliding speed of 0.251 m/s and different axial loads.

The model friction pair uses a receiving device as a slit with rounded edges to measure the pressure in the contact area. Local pressures in the contact zone were determined by scanning along the entire length of the contact (Fig. 4, b). The scan length, speed, and test coordinate are set in the program and controlled accordingly. After analyzing the results shown in Fig. 4, there is a natural decrease in pressure in the confuser contact area and an increase in the degree of rarefaction in the diffuser area [26, 35].

4 Results and Discussion

The study of the formation of the air-gas phase in the environment of diesel fuel was performed by modeling. Thus, a layer of diesel fuel (painted dark with 80W–90 oil) was applied to the polished surfaces made of 100Cr6 steel and quartz glass. When compressing these surfaces, the studied medium's extrusion into the studied surfaces' microrelief was observed, and when the load was removed, gas cavities in the boundary layer were formed (Fig. 5).

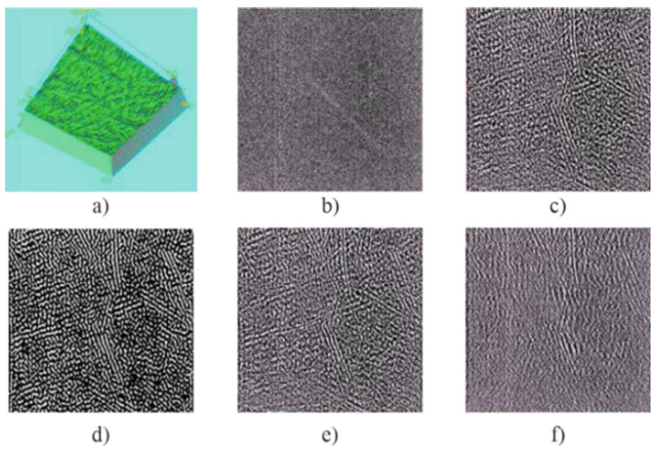
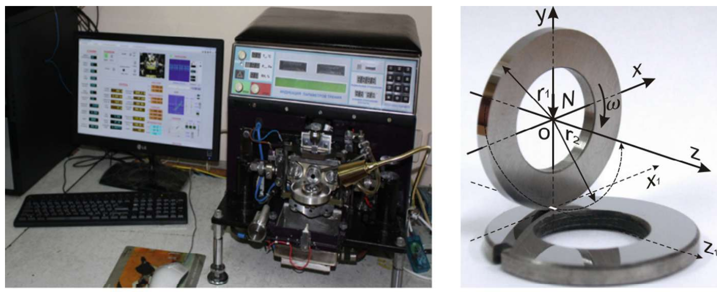


Fig. 5. Formation of planes with boundary layers of opaque lubricating medium between polished surfaces 100Cr6 - quartz: a) the general appearance of the polished surface; b) compressed surfaces with a force of 1.0 MPa; c) compressed surfaces with a force of 5.0 MPa; d) compressed surfaces with a force of 10.0 MPa; e) the surface 10 min after unloading; f) surfaces 24 h after unloading.

The studies were performed on LDPMP. After surface compression to 1.0 MPa, the contact of the surface roughness vertices of steel and quartz samples was observed (Fig. 5, b), and the contact area was about 40% of the contour contact area. When the load increases to 5.0 MPa, common planes with remnants of the opaque lubricating medium are formed between the elastically deformed vertices (Fig. 5, c). Further increase in the load to 10.0 MPa led to some expansion of the area of the contacting vertices and a decrease in the area of the cavities filled with lubricating medium (Fig. 5, d). When visually assessing the total contact area, in this case), it was increased to 60%. After the load was removed, there was a slow increase in the volume of lubricating media (Fig. 5 e, f). It should be noted that after removing the load of 10 MPa, even after 24 h, the adhesion forces between the surfaces were so strong that it was possible to separate them only by shifting them. This study allows us to explain the contact interaction of high-pressure fuel pumps' precision surfaces and make new assumptions about improving their performance.

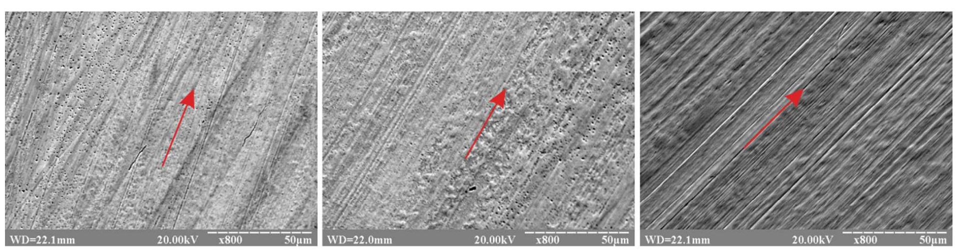
Research on friction and wear of selected lubricants was performed on a laboratory friction device ASK-01M with linear contact (Fig. 6, a), the design features of which allow providing constant instantaneous contact stresses. Ensuring constant contact stresses is because all the studied parameters of tribocontact: the point of friction, load axis, the axis of rotation of the model shaft, and the axis around which the fixed flat sample oscillates, intersect at the center of masses of the counterbody (Fig. 6, b). The friction device controls the radial deviations of the counter-sample. The tests were carried out by mutual contact of surfaces of 100Cr6 steel in the environments of aviation gases and diesel fuels of different delivery series, considering the secondary structures (Fig. 6).



a) b)

Fig. 6. General view of the friction machine with linear contact ASK-01M a) and a model sliding tribosystem that provides constant instantaneous contact stress b).

At the initial stages - 500 m of friction path (Fig. 7 a, b), secondary structures were developed (the so-called running-in period). In Fig. 7 c), quasi-stable secondary structures are obtained, which were obtained after running in (3000 m of friction). The arrows show the direction of friction.



a) b) c)

Fig. 7. General view of friction surfaces (magnification × 800) with developed secondary structures: a, b) in the initial stages; c) quasi-stable after the running-in process.

The test results of lubricants (aviation and diesel fuels) selected for research are shown in Fig. 8. The amount of wear was measured on an LDPMP. The results are presented as the dependences of wear I, µm on the friction path L, m of polished surfaces of 100Cr6 steel in selected test media.

As shown in Fig. 8, environment No. 5 has the best antiwear properties. The wear of the surfaces, when used for lubrication of the samples of the studied environments No. 2, No. 3, and No. 4 differs insignificantly (within 0.2 µm). However, the intensity

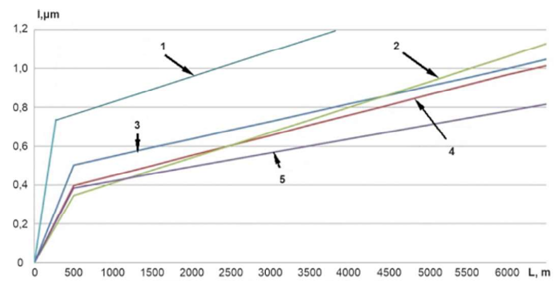


Fig. 8. The results of studies of antiwear properties of selected lubricants: 1, 2, 4 - diesel fuels from different manufacturers and different series of deliveries (selected at random); 3–5 - aviation gasoline TC-1 of different series of delivery (selected at random).

of wear in environment No. 2 is relatively high, compared to the intensity of wear on friction surfaces in environments No. 3 and 4.

Therefore, media No. 2–5 can be recommended as working media for use in operational conditions to lubricate high-precision tribo-units with small clearances (for example, a high-pressure fuel pump). When using sample No. 1, it is advisable to consider the machine's operating conditions in more detail since the anti-wear properties of this environment are low, compared to others studied in our work.

5 Conclusions

The recommended option to increase the efficiency, durability, and other operational parameters of complex high-precision products with precision tribosystems, in particular plunger pairs of high-pressure fuel pumps, is the use of a comprehensive experimental scientific and methodological approach. Experimental studies show that to increase the wear resistance of precision tribo-surfaces of plunger pairs, it is necessary to pay special attention to their microrelief (including its spatial configuration) and create appropriate technologies for their manufacture and control. One of the options for technological quality management of functional surfaces of plunger pairs is the development of high-tech operations and introducing additional finishing and strengthening operations. This will create microgemetric parameters, the configuration of the surface layer, which will not have the phenomenon of setting at the running stage in surfaces and temperatures below –20 °C.

According to the results of these studies, the wear resistance of friction surfaces and the range of operating temperatures depends on the properties of lubricating media. Particularly, when developing the technology for machining the parts of the plunger pair, the following statements should be taken into account:

1. Phase transformations in the boundary layers of lubricants – because they depend on the stage of nucleation of the gas-air mixture;
2. Dynamic phenomena in the boundary layers of lubricating media affect the state of dynamic equilibrium in the contact zone and the initialization of the process of tribocavitation. The conducted studies show that with a change in only the speed of

rotation of the movable couplings within 0.12…0.04 m/s, the maximum contact pressures change by 30 kPa (20%), which affects the wear resistance and the possibility of adhesion of the friction surfaces;

3. Backflows and heat flow in friction dynamics - leading to the formation of zones with insufficient oil film thickness and, as a result, oil starvation, especially taking into account that the contact contour area can vary by 20% or more depending on the contact pressures;
4. Viscosity-temperature and antiwear characteristics directly affect the service life of the friction assembly. Considering that the wear of surfaces in the same type of lubricating media (Fig. 8) differs by almost 50%, to ensure the necessary durability of specific high-precision products, it is advisable to recommend using only certain lubricating media of proven manufacturers.

The conducted research is a prerequisite for developing scientifically based recommendations for improving the design features of products, choosing methods for processing friction surfaces, and creating an engineering methodology for assigning processing modes. This approach will allow to expand the regulatory limits of high-pressure fuel pumps and predict the resource of their trouble-free operation.

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