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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

ENHANCING THE RELIABILITY OF PRECISION COMPONENTS THROUGH LASER TECHNOLOGICAL METHODS

Speciality:	3310.01 - Industrial technology
Field of science:	Technical sciences
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GENERAL CHARACTERISTICS OF THE WORK

The relevance and degree of depelopment of the topic. In modern times, chemical-thermal treatment has been increasingly preferred for the surface strengthening of precision components of machines and equipment. This is explained by several factors, the most significant of which are: the higher efficiency of laser technology as one of the chemical-thermal methods, its ability to process any surface, and the reduction of processing time due to accelerated treatment. At the same time, the application of new and modernized laser technologies with high specific power has reduced energy consumption. The use of such laser technologies makes it possible to increase labor productivity, which is of particular importance.

The solution to the above-mentioned problems, as shown by preliminary studies, is to increase the surface hardness of precision parts of machines and devices using laser technology and complex diffusion metallization in vacuum. In this case, these methods can be applied not only to improve the durability of the working surfaces of precision components but also as a means of restoring the parts.

The issue of using laser technology in vacuum conditions to enhance the surface hardening of friction pair components operating under abrasive wear and high-temperature conditions has not been practically studied. In the “plunger–pusher bolt” pair (contact surface), the surface layer is subjected to the most intensive mechanical, impact-abrasive, hydro-abrasive, thermal, and other effects under operating conditions.The analysis of the problem of improving the operational reliability and durability of the working surfaces of the fuel pump plunger and the “plunger–pusher bolt” tribological pair shows that, at present, extending their service life cannot always be achieved solely through the use of expensive high-alloy steels or by applying conventional surface strengthening methods.

The technological advantages of laser surface treatment include localized and contactless heating, the absence of deformations (bending), high processing speed and productivity, the ability to treat hard-to-reach areas, adaptability to automation, as well as reduced electrical energy consumption compared to frequently applied processes such as high-frequency current treatment, nitriding, carburizing, vacuum diffusion metallization, and nitrocarburizing.

Despite numerous studies, the influence of technological parameters of the laser surface hardening process on the tribological properties of surface layers under various friction and wear regimes has not been sufficiently investigated. In general, the effect of laser surface hardening in vacuum on the characteristics of tribological joints has not been studied. Only a limited number of works have been devoted to laser surface hardening aimed at improving the wear resistance of tribological pairs. Virtually no information is available on the application of laser processing for the surface modification of precision components operating under impact-abrasive and hydro-abrasive conditions.

Research aimed at developing new technological processes and methods for hardening the working surfaces of fuel pumps is of particular relevance in enhancing their operational performance.

The aim and objectives of the research are to conduct a comprehensive investigation of the formation regularities of surface layers during laser processing of plungers in the highly loaded "plunger–barrel" pair and the "plunger–pusher roller" pair of fuel pumps operating under various friction and wear conditions; to study their inheritance; to examine their key properties under real contact interaction conditions; and, on this basis, to develop scientifically substantiated recommendations for obtaining surface layers with enhanced tribological characteristics..

Achieve this goal, the following research objectives were addressed:

1. To investigate the regularities of the formation of geometric parameters and main characteristics in the hardening of surface layers of fuel pump tribological components by laser treatment in vacuum;
2. To study the influence of laser processing regimes, the initial structure of the material, and surface roughness on the antifriction and wear-resistant properties of various tribological pairs;
3. To develop scientifically substantiated recommendations for the selection of optimal regimes of laser processing in vacuum,

ensuring the purposeful formation of surface layers with high tribological properties under specific operating conditions;

4. To develop methods for evaluating the tribological properties of surface materials in terms of structure and wear resistance, aimed at ensuring the reliability indicators of precision joints through changes in geometric dimensions;

5. To elaborate recommendations on the application of vacuum laser surface hardening to enhance the operational reliability and durability of the plunger in the "plunger–barrel" pair and the "plunger–pusher bolt" assembly of fuel pumps;

Main provisions submitted for defense. Based on the conducted research, the following key provisions are put forward for defense

1. The substantiation of abrasive and impact-abrasive wear of precision components, the development of scientific foundations for the use of laser technology to improve the wear resistance of precision pairs, the introduction of a new technological process for laser surface strengthening of fuel pump precision parts, and the experimental results for evaluating this technological process;
2. The high-rate heating and cooling of the surface layer of precision components, along with the short exposure time, provide conditions for achieving optimal structure and properties in the treated surface;
3. The ability to regulate the parameters of laser processing enables the purposeful formation of the structure, physico-mechanical properties, roughness, and geometric dimensions of the treated surface layers.

Object of the research: precision components of fuel pumps — the plunger and the "plunger–pusher bolt" joint (ХВГ; ШХ15; 25Х5МА - steel).

Research methods and reliability of results. The objectives of the dissertation were addressed through theoretical and experimental studies carried out under laboratory and industrial conditions. The reliability of the obtained results is confirmed by the use of modern equipment and instruments in experimental investigations, the processing of experimental data using mathematical statistics methods with computer support, as well as by comparison with the individual findings of other authors.

Scientific novelty of the research.

1. For the first time, the laser method in vacuum was theoretically substantiated, a device was designed, and a technological process was developed for hardening the surfaces of precision components of fuel pumps — two patents were obtained [1, 16];
2. The mechanisms of abrasive and impact-abrasive wear were studied, and a new model of thermal processes in vacuum laser hardening of precision component surfaces was proposed; stress and deformation changes caused by irradiation heating in precision parts were investigated [2, 3, 12];
3. Diffusion saturation regimes ensuring the greatest increase in linear dimensions were optimized [5, 9, 13];
4. The physico-mechanical properties and metallography of precision joints were examined [14, 15];
5. The tribological and operational characteristics of precision components with strengthened surfaces were studied [4];

Practical significance and industrial application of the research. A new technology for surface strengthening of the tribological components of fuel pumps has been developed and recommended for industrial application. The implementation of this technology enables the purposeful formation of high-quality layers on the working surfaces of the plunger and the “plunger–pusher bolt” assembly of fuel pumps.The technology for enhancing the surface harden of precision components of machines and equipment has been submitted for application to the “NeftQazMaş” plant. It has been established that laser surface hardening of fuel pump precision parts increases their performance capacity by 2–3 times.

Approbation and application. The main provisions of the dissertation were discussed and approved at the following conferences and seminars, and they also underwent approbation within the instruction of courses at Azerbaijan Technical University in the specialties XTM 060002 “Optical Engineering” and XTB 050106 “Weapon Systems Engineering”; they have been implemented in the teaching process, and a textbook entitled “Fundamentals of Tribology” has been developed.

1. IX Republican Scientific and Technical Conference of Students and Young Researchers on Progressive Technologies and Innovations dedicated to the 101th Anniversary of Heydar Aliyev’s birth, Baku, 1-2 may, 2024.
2. X Republican Scientific and Technical Conference of Students and Young Researchers on Progressive Technologies and Innovations dedicated to the 102st Anniversary of Heydar Aliyev’s birth, Baku, 1-2 may, 2025.
3. VI International Turkic World Congress on Science and Engineering, December 19–21, 2024, Azerbaijan Technical University, Baku, Azerbaijan.
4. XX International Scientific and Practical Conference Innovative Scientific Research: Latest Theories, Modern Methods and Practices, May 20–23, 2025, Seville, Spain.
5. Ə. G. Hüseynov, Ş. N. Əsədov və F. S. Hüseynli, Tribologiyanın əsasları. Bakı: KİNGPRİNT, 2024. 262 pp.

Overall, the main content of the dissertation has been reflected in 16 scientific works, 3 of which were published in high-impact journals indexed in the Scopus database. In addition, one patent has been granted (AzPatent No. İ 2025 0055), another has received a publication decision (AzPatent No. a 2023 0076), and one textbook has been prepared. The remaining works were published in international and national conferences.

The total volume of the dissertation in characters, indicating the volume of the structural sections of the dissertation separately. The dissertation as a whole comprises 196 pages. The overall volume of the work consists of 57 figures, 5 tables, an introduction, 5 chapters, general conclusions, and a list of 148 references. The length of the dissertation - excluding spaces and figures in the text, appendices, and the reference list is 228,336 characters. Title page - 337 (1 p.); Table of contents - 4,337 (3 pp.); Introduction - 9,361 (4 pp.); Chapter I - 57,772 (32 pp.); Chapter II - 48,173 (39 pp.); Chapter III — 8,055 (9 pp.); Chapter IV - 61,476 (48 pp.); Chapter V - 44,668 (35 pp.); Conclusions - 3,917 (2 pp.); References - 30,276 (17 pp.).

DISSERTATION SUMMARY

The introduction presents the relevance of the dissertation topic, the main provisions submitted for defense, the scientific novelty, the practical significance, and the reliability of the methods and results.

In the first chapter, a literature review was conducted, and studies aimed at ensuring the reliability of the tribological joints of fuel pumps were summarized. Particular attention was given to the causes of failure of precision pairs, ensuring the reliability of working surfaces, and the technological requirements imposed on them. The impact of surface hardening on the durability of tribological joints was analyzed, along with the influence of the quality, physico-chemical state, and properties of the surface layer on load-bearing capacity and wear resistance. Furthermore, methods of enhancing the surface harden of tribological components, including the potential of laser processing, were also examined.

To study the wear mechanisms of precision components of fuel pumps, references were made to the works of I.V. Kragelsky, M.M. Tenenbaum, M.M. Khrushov, M.L. Babichev, B.I. Kostetsky, N.I. Bakhtiyarov, as well as A.G. Huseynov and Academician Ahad Janahmadov. In addition, the processes of impact-abrasive wear were analyzed using the fundamental studies of Georgiy M. Sorokin, which play a distinctive role in tribology. V.V. Antipov paid particular attention to issues of improving operational performance.

In the field of reliability assurance and restoration technologies, the research of V.N. Bugaev, K.A. Achkasov, Yu.V. Mazaev, V.Z. Sergeev, E.A. Davidenko, B.A. Bogachev, as well as S.H. Babayev and A.G. Huseynov, were reviewed.

Regarding laser surface hardening, in addition to the investigations of local scientist A.M. Hajiyev, international research by Lin Li, Andrés Fabián Lasagni, and Y. Lawrence Yao on laser surface structuring, micromechanical effects, and laser processing technologies was also taken into account.

The results of the analysis show that a significant share of failures in fuel pumps is associated with the wear of precision tribological pairs (the plunger and the “plunger–pusher bolt” pair), accounting for approximately 41.7% of total malfunctions, while about 30% of general failures are related to tribological assemblies. Typical defects include the loss of hydraulic sealing in the plunger–barrel pair, reduced mobility of the plunger, and impact wear or damage in the plunger and "plunger–pusher bolt" pair. As a result, the service life is reduced on average by ~20%, fuel consumption may increase by 10–15%, and the actual lifespan of the plunger–pusher bolt pair ranges from 200 to 1500 engine hours (approximately 20–25% of the manufacturer's warranty).

A comparative analysis of surface hardening methods shows that types of chemical-thermal treatment—such as nitriding, carburizing, nitrocarburizing, carbonitriding, and titanizing—significantly increase the hardness and fatigue limit of precision components. However, due to increased brittleness in diffusion layers and reduced impact resistance, the selection of optimal processing regimes is of particular importance. Surface plastic deformation methods (such as diamond polishing, roller polishing, etc.) can introduce residual compressive stresses and raise the fatigue limit by 15–30% or even more. High-energy and diffusion-based methods, including thermomechanical treatments, electron-beam and arc alloying, and ion implantation, also enhance wear resistance by refining and densifying the structure. Nevertheless, when applied to precision surfaces, these technologies have certain limitations in terms of dimensional accuracy, shape stability, and brittleness balance. For optimal results, the choice of technology must be aligned with the material properties, working conditions, and operational requirements.

In the first chapter, a literature review was conducted, showing that the performance of fuel pumps is primarily determined by the quality of the working surface and the characteristics of the surface layer that maintains its stability during operation. Although laser technology is considered a promising innovative and highly controllable localized heat source, fully developed technological regimes for precision tribological assemblies operating under variable loads and thermal conditions have not yet been established. In particular, studies on the application of laser surface hardening to the plunger and the "plunger–pusher bolt" pair are almost non-existent, and reliable testing methodologies for such heterogeneous materials remain insufficiently developed.

Thus, despite the existing scientific foundation and practical experience, there remains a need for comprehensive theoretical and experimental studies of the processes occurring in the surface layer after laser surface hardening in the tribological joints of fuel pumps, as well as the conditions for the purposeful formation of layers with high tribological performance. These gaps define the aim and objectives of the present research. For this reason, the development and application of laser surface hardening technology is regarded as one of the most promising approaches to enhancing the wear resistance of precision components.

In the second chapter, the theoretical foundations of laser technology for ensuring the reliability of fuel pump precision assemblies through surface hardening are summarized. The chapter explains the thermal phenomena occurring during laser processing of key precision joints, the geometric parameters of the strengthened layers and their variations, as well as the calculation of layer dimensions based on the overlap coefficient (K_n). The procedures for calculating layer parameters in the case of precision components manufactured from tempered steels are presented, and the possibilities for predicting the reliability of precision components are examined.

Theoretical investigations are presented in detail in the dissertation. The thermal processes involved in enhancing the surface hardness of fuel pump precision joints using laser technology were analyzed. It can be assumed that the propagation of heat in the metal during laser treatment can be explained on the basis of the classical principles of heat conduction theory. The thermo-physical characteristics of the material of precision components include the thermal conductivity coefficient (λ), which determines the ability to transfer heat from the surface heating source generated by laser irradiation. At the same time, the volumetric heat capacity (cγ), which defines the intensity of the heat flux, plays an important role. The complex indicator of thermo-physical properties is the thermal diffusivity, expressed as $a = \frac{\lambda_T}{c\gamma}$.

The generalization of the conducted research makes it possible to determine the influence of various factors on the nature of structural and phase transformations of laser-processed material, its properties, as well as the geometric parameters of the heat-affected zone. In calculations for precision components, the average values of these coefficients are assumed as follows: $\lambda_T = 0.38\ldots0.42$ C/(cm·s)·degree; $c\gamma = 4.9\ldots5.2$ C/(cm^3); $\alpha t = 0.075\ldots0.09$ cm^2/s. When the beam power density is in the range of 10^2–10^5 W/cm^2, the laser can be regarded as an equivalent heat source. The process of heat propagation from an instantaneous local source Q at the initial moment t = 0 can be expressed by the following equation:

$$T(R,t) = \frac{2Q}{c\gamma(4\pi\alpha t)^{3/2}} e^{-\frac{R^2}{\alpha t}} + T_0, \tag{1}$$

where, T is the temperature at the investigated point; t is the time elapsed after the application of the heat source; $R = x^2 + y^2 + z^2$ is the square of the distance from the heat source (Q) to the investigated point; $\alpha = \lambda_T / c\gamma$ is the thermal diffusivity (temperature conductivity) coefficient; T_0 is the initial temperature of the material before laser processing.

In the process of laser thermal hardening under continuous irradiation, when the focused beam moves uniformly over the treated surface at a velocity V, the maximum temperature at the center of the laser beam spot on the surface can be determined by the following formula:

$$T_{\max} = \frac{q_\Phi r}{\lambda_T}\left(1 - \frac{Vr}{2a}\right), \tag{2}$$

Experimental data show that absorption occurs within a layer of $(5 \div 80)\cdot10^{-3}$ µm in thickness, while the propagation of heat into the depth of the material takes place through thermal conductivity.

Taking into account the heat transfer into the depth, an equation relating the hardening depth Z to the hardening temperature T has been derived, and the following condition must be satisfied during laser hardening:

$$Z = \left[\frac{2\sqrt{a\tau}}{\sqrt{\pi}} - \frac{\lambda\tau T}{\varepsilon(1-R)}\right] \tag{3}$$

where, a, λ, and R are the coefficients of thermal diffusivity, thermal conductivity, and light reflectivity, respectively; ε is the power density of the laser radiation, which corresponds to the power density at which the surface temperature of the material reaches T. During laser processing, the strengthening of precision components occurs when the power density is in the range of 10^2–10^5 W/cm^2 and the irradiation time is approximately $\tau = 10^{-3}\ldots10^{-7}$ seconds.

The heat energy absorbed in the surface layer of the material, as well as the amount of absorbed energy varying with the distance Δx from the surface, are expressed by the following equations:

$$E(x) = E_0(1-R)e^{-\alpha x}, \tag{4}$$

$$E(x) = E_0(1-R)2e^{-\alpha x} \cdot \Delta x. \tag{5}$$

where, E(x) is the heat energy absorbed in the surface layer of the material; E_0 is the irradiation energy of the surface; R is the specific reflectivity; and α is the absorption coefficient of energy. The analysis based on equations (4) and (5) shows that energy absorption reaches its maximum directly near the surface and gradually decreases with increasing depth. This explains the reduction in microhardness of the hardened layer as the distance from the surface increases.

The theoretical results obtained were verified by experiments and presented in the dissertation in the form of graphs.

For pre-hardened precision components of fuel pumps during processing, the area of the tempering zone is expressed by the following formula:

$$A_0 = \frac{h_0}{15}\left[6ϐ_0 + 8\sqrt{h_0^2 + (0.5ϐ_0)^2}\right] - \frac{h}{15}\left[6ϐ + 8\sqrt{h^2 + (0.5ϐ)^2}\right] \tag{6}$$

where, the depth of the laser hardening zone (LHZ) is denoted by h; the width of the LHZ by ϐ; the radius of the circular segment by R; the width of the laser-affected zone (LAZ) by $ϐ_0$; the depth of the LAZ by h_0; and the radius of the LAZ circular segment by R_0.

The reliability prediction of laser surface-hardened precision components of fuel pumps has been investigated. The conditional distribution density of failure-free operation time (λ(t)) as well as the wear intensity (λ(n)) have been determined. They are expressed by the following formula:

$$\lambda(n) = P(\hat{u} > \hat{x}/\hat{A}(n)) = \int_{-\infty}^{\infty} \frac{F_{\hat{u}}^{n}(x) R_{\hat{u}}\, dF_{\hat{x}}(x)}{\int_{-\infty}^{\infty} F_{\hat{u}}^{n}(x) dF_{\hat{x}}(x)} \tag{7}$$

where, n is the number of tests; x̂/Â(n) is the conditional random variable of parameter x̂ after n tests under the condition A(n) that no failure occurs in those n tests; $F_{\hat{u}}$(x) and $R_{\hat{u}}$(x) are the distribution and reliability functions of the random variable, while $F_{\hat{x}}$(x) is the distribution function of performance indicators; t is the next time unit during which the object continues to operate without failure up to the moment of failure intensity; and P(û > x̂/Â(n)) represents, at the first interaction of the prediction, the probabilities of failure and failure-free outcomes, respectively.

As a result of the approximation of the experimental H(z) dependencies, an analytical expression was obtained that describes the regularities of microhardness variation along the layer thickness under optimal processing regimes:

$$H = \frac{Hn_l}{\left[\left(\frac{Hn_l}{Hc_0} - 1\right) \cdot \left(\frac{Z}{hc_l}\right)^4 + 1\right]}, \tag{8}$$

where, Hn_l and $Hc_0$are the values of microhardness at the surface and at the core of the base metal, respectively; hc_l is the thickness of the hardened layer, measured from the surface to the region characterized by constant hardness corresponding to the core hardness level of the component; and Z is the current coordinate of a point within the layer.

Thus, the analysis of hardness variation patterns suggests that, in selecting the laser hardening regime, the priority should be to ensure a level of microhardness characteristics that guarantees the resistance of fuel pump precision components to fracture and wear under real operating conditions.

The studies conducted in this chapter demonstrate that, under laser exposure in precision tribological joints of fuel pumps, rapid heating and intensive heat transfer generate high energy fluxes that induce characteristic structural transformations. The conditions for the formation of the surface layer are determined by the chemical composition and thermo-physical properties of the material, as well as by the power density of the laser and the processing regimes. The geometric dimensions of the hardened layer depend on the thermo-physical characteristics of the treated metal, the radiation power density, and the scanning velocity of the laser beam across the surface.

In the third chapter, the experimental methodology employed by the author is presented.

The research was carried out at the laboratory of “Diffusion Metallization and Technology of Special-Purpose Products” of the Azerbaijan Technical University using a patented vacuum laser diffusion unit developed by the author (Figure 1). The working surfaces of the fuel pump precision components — the plunger and the “plunger–pusher bolt” joints — were selected as the objects of study. The unit was modified on the basis of the СНВ-131/16И4 type vacuum chamber resistance device prototype.

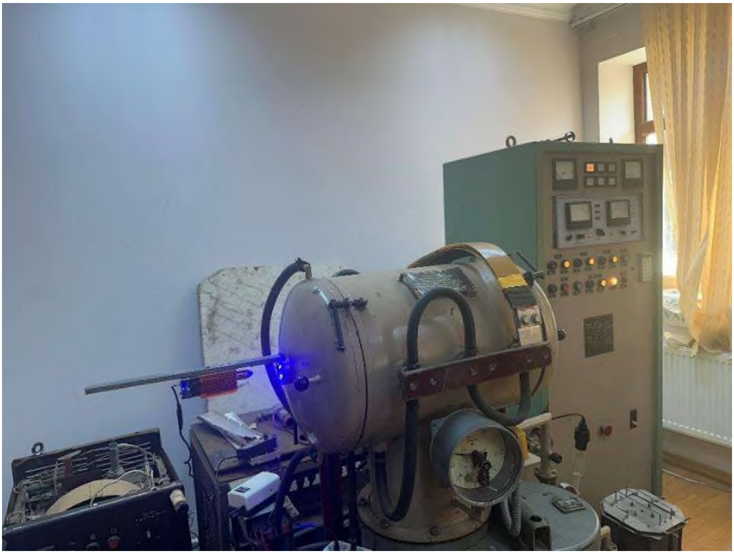


Figure 1. Vacuum Laser Diffusion Metallization Unit.

To evaluate the roughness of the cleaned surface, a profilograph–profilometer model 253 was used.

Measurements of the plunger and the “plunger–pusher bolt” were carried out on an “ОГП” optical device with a scale division of 0.0002 mm; taper and ovality were measured on an “E-92IA” rotameter and on a “Talyrond 200” instrument. Taper, ovality, cylindrical form, and selected groups were also determined using an “0П286” type optical device. The degree of wear was determined on the mentioned instruments through micro-measurements. Measurements of the plunger and the “plunger–pusher bolt” were performed at five cross-sections and in two mutually perpendicular planes in accordance with the manufacturer’s micrometric specifications.

Metallographic analysis was carried out on cross-sections prepared from micro-polished samples or specimen parts. All micro-polished samples were prepared in accordance with standard methodology and examined using established methods. Both straight and inclined sections were analyzed.

The hardness of the sample components was determined using a TKC–1M measuring device according to the Rockwell and Brinell methods.

In accordance with ГОСТ 9450-76 (standard SEB I95-78), microhardness measurements were carried out on a PMT-3M device using the Vickers method, with the values determined as Hμ.

The microstructure and phase composition were studied on metallographic sections and with an SEM microscope, both before and after processing.

The tribological properties were evaluated on an ИИ-5018 friction machine using the “pad–roller” scheme and processed by the method available at the Department of “Special Technologies and Equipments”.

The fourth chapter is devoted to laser surface hardening of the tribological joints of fuel pumps under vacuum conditions. It examines the changes in the geometric dimensions of precision components, the microhardness and hardness indicators after hardening, the correlation between operational factors and the requirements imposed on surface layers, the effect of laser track overlap on the reliability of the assembly, the selection of the optimal overlap coefficient, as well as the influence of laser regimes on the parameters of the tribological layer, particularly the characteristics of the hardened layer formed in ХВГ steel.

The physico-mechanical properties of laser surface-hardened precision components were investigated. Analysis of the wear measurements of plunger surfaces shows that the distribution of these values follows the Weibull law. The mean wear value is t^{-} = 13.119 µm, with t^{B} = 27.30 µm and t^{H} = 1.856 µm. The standard deviation is G = 12.123 µm, and the coefficient of variation is V = 0.906. The analysis of the roughness of precision surfaces of tribological joints after operation indicates that, for slightly worn surfaces, the roughness R_a varies within 0.04…0.05 µm, while in localized wear areas it reaches 1.22…1.42 µm, where traces of abrasive effects are clearly observed.

The effect of parameters on the layer thickness during laser hardening was analyzed. Preliminary experiments were carried out to determine the changes in geometric dimensions. As a result of these experiments, dependencies were established for vacuum diffusion boron–titanizing, vacuum diffusion titanizing, and vacuum laser hardening processes regarding the influence of time and temperature on surface roughness and the thickness of external and internal surfaces. Our studies show that although roughness is low below 1000 °C, the linear dimensional growth is insufficient for the complete strengthening of the worn plunger and the “plunger–pusher bolt” pair (Figure 2). It was noted that surface roughness was highest in vacuum diffusion boron–titanizing, lower in diffusion titanizing, and lowest (i.e., best results) in laser surface hardening. At temperatures above 1200 °C, surface roughness increases sharply.

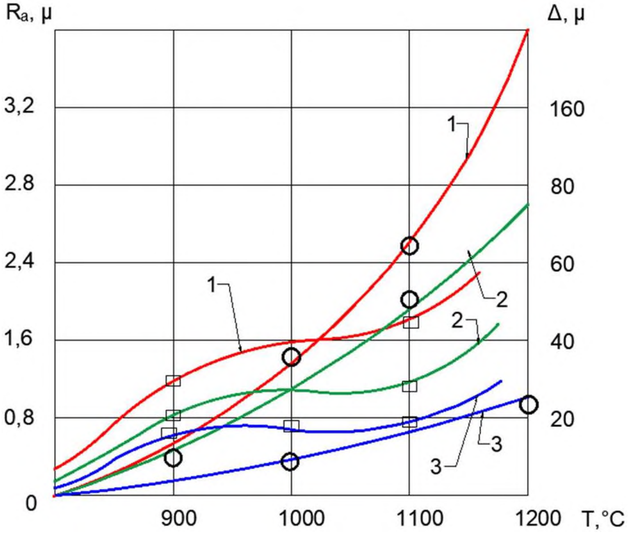
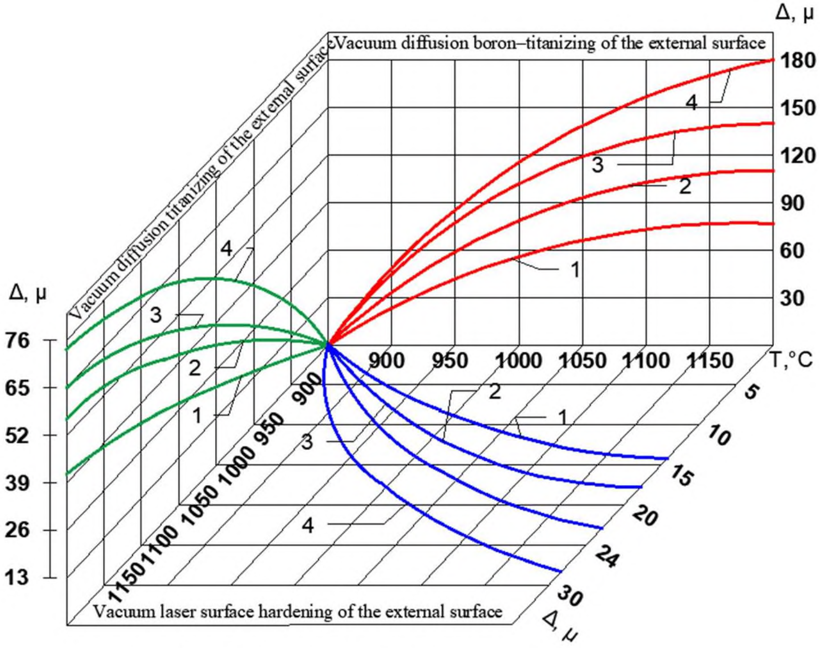


Figure 2. Dependence of surface roughness R_a (□- □) and linear dimensions Δ (o–o) of components on temperature during vacuum diffusion boron–titanizing (1), vacuum diffusion titanizing (2), and vacuum laser surface hardening (3).

Figure 3 illustrates the dependence of the hardened layer thickness (Δ, µm) on temperature and processing time for external surfaces. Our research shows that the hardened layer thickness on the external surface formed by boron–titanizing, titanizing, and laser hardening is 180 µm, 74 µm, and 26 µm, respectively. In laser hardening, approximately two-thirds of the total layer forms internally and one-third externally, with the microhardness of laser-hardened layers ranging between 21.2–22 GPa. As a result, laser hardening, being a localized and rapid technology, maintains its effectiveness even under high-temperature conditions. The dissertation provides a detailed study of the dependence of geometric parameters on temperature and time, as well as their effect on surface roughness indicators, for vacuum diffusion boron–titanizing, diffusion titanizing, and laser hardening applied to internal surfaces. In laser hardening, the technological process duration is 2–8 seconds; as the duration increases, R_a rises slightly, with the optimal interval being 4–8 seconds, while longer durations are considered impractical.



Laser processing regimes:
P= 1.25 kVt;
d_n= 3 mm;
V= 5 mm/s;

Figure 3. Variation of geometric parameters on the external surface during vacuum diffusion boron–titanizing, diffusion titanizing, and laser hardening as a function of temperature and time (respectively: 1 – 4 h; 2 – 5 h; 3 – 5.5 h; 4 – 6 h; for laser hardening: 1 – 4 s; 2 – 5 s; 3 – 5.5 s; 4 – 6 s).

The study of the dependence between the duration of the technological process and the thickness of the hardened layer (Δ) shows that, since laser surface hardening occurs on a scale of seconds, the layer forms thin: approximately ~18 μm in 2–4 seconds and ~26 μm in 6–8 seconds. The same tendency is observed on the internal surface, although in diffusion methods the thickness is lower compared to the external surface (Figure 4). As a result, boron–titanizing is more suitable for obtaining a thick layer, titanizing for achieving controlled thickness and corrosion resistance, and laser processing for dimensional accuracy and rapid treatment.

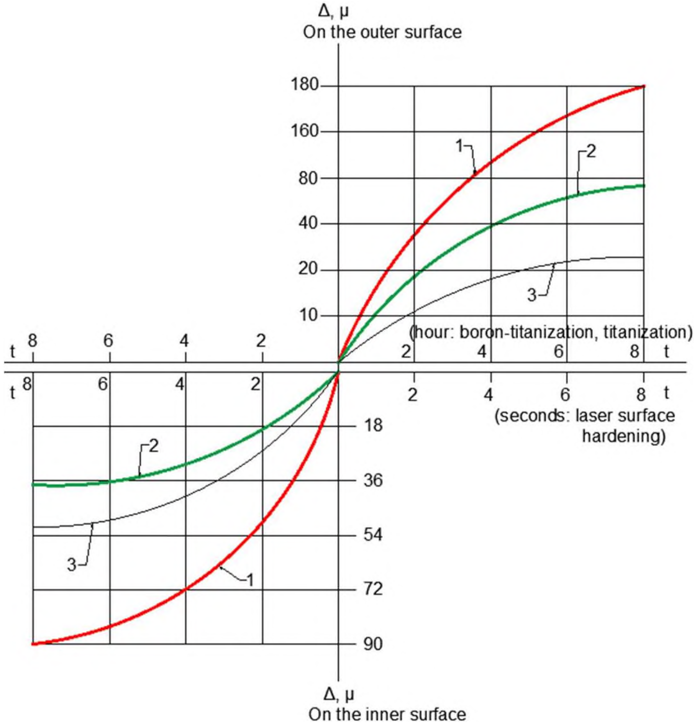
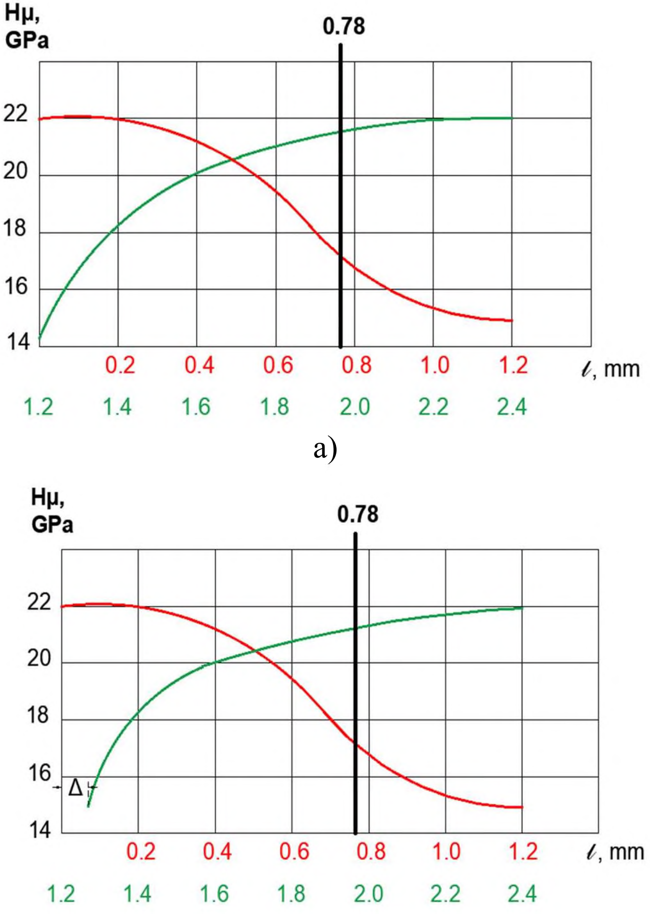


Figure 4. Variation of hardened layer thickness (Δ, μm) of external and internal surfaces in boron–titanizing, titanizing, and laser surface hardening processes as a function of process duration (t). 1 – Boron–titanizing (t in hours); 2 – Titanizing (t in hours); 3 – Laser surface hardening (t in seconds).

As shown in Figure 5(a), when the overlap coefficient K_n is low, unstrengthened areas remain in the regions of partial track overlap during laser processing, where the microhardness values practically do not differ from the initial microhardness level of the base metal. When the overlap coefficient increases to the level of $k = 0.5 \cdot d_n$ (Figure 5b), hardened and tempered areas with martensitic and troostitic structures are observed on the hardened surface of the precision component. The width of the tempered zone, with reduced microhardness down to 19 GPa, is approximately 0.4 mm. The studies showed that the formation of areas with decreased microhardness in the surface layer is associated with reheating of these zones to the tempering temperature.



a)

b

Figure 5. Microhardness distribution across the laser-hardened surface of fuel pump precision components: a – processing with S = d$_f$; b – processing with overlap; 1 and 2 – the first and second laser tracks.

The generalized graphs in Figure 6 illustrate the variation of the geometric dimensions of the hardening and heat-affected zones, as well as the average microhardness of the hardening zone, depending on the laser processing speed in the tribological pairs of fuel pumps.

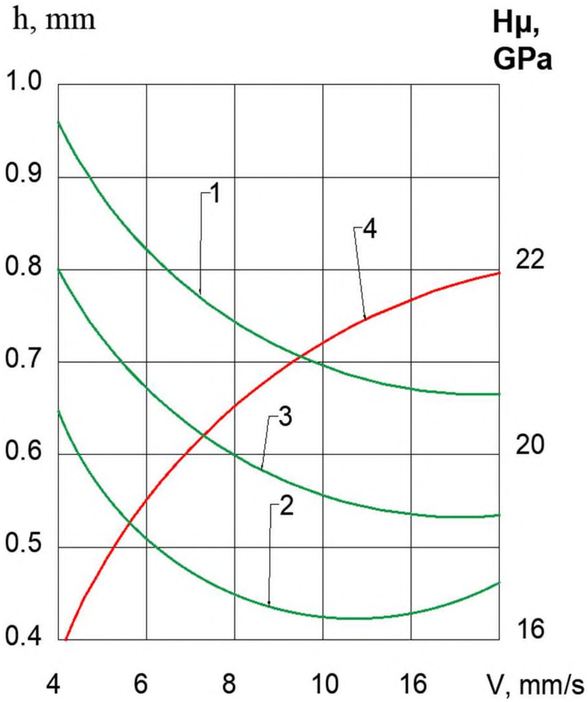


Figure 6. Dependence of the dimensions of laser-affected zones and microhardness on processing speed in precision components:

1 – width of the hardening zone; 2 – depth of the hardening zone; 3 – depth of the heat-affected zone; 4 – microhardness of the hardening zone.

Metallographic analysis of surface-hardened precision components was carried out. Experimental studies revealed that in the laser-hardened layers of samples and parts made of ХВГ steel, the microhardness varies within the range of 1200…2200 HV (approximately 12.2…22 GPa). As shown in Figure 7, in the laser method, the surface microhardness decreases sharply from about 22 GPa at the surface to 12.2 GPa at a depth of 26 μm and stabilizes at the base metal level (~11.8 GPa) after ~52 μm. This indicates that the layer is thin with a sharp boundary and minimal influence on the base metal. The generalized results demonstrate that, although laser hardening produces a thinner layer, it ensures higher surface hardness, shorter processing time, a narrower heat-affected zone, and minimal deformation. Therefore, boron–titanizing is considered more suitable for parts exposed to a high risk of deep wear, whereas laser surface hardening technology is more appropriate for parts requiring high precision and minimal deformation.

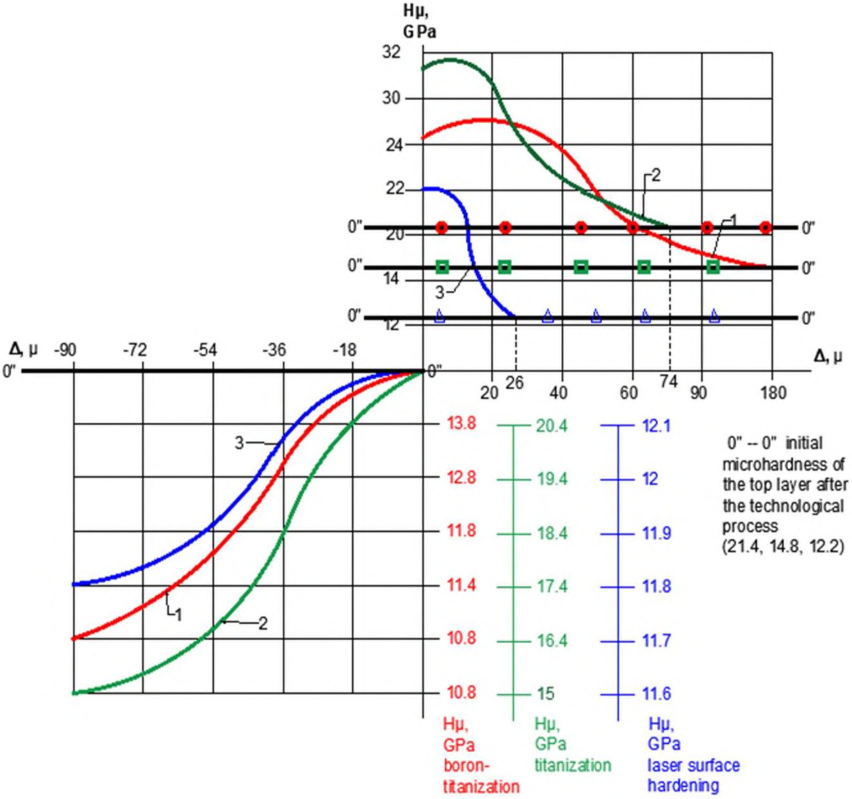


Figure 7. Depth profile of microhardness variation in the tribological components of fuel pumps after different surface hardening methods. "0–0" indicates the initial surface microhardness after the technological process (21.4, 14.8, and 12.2 GPa, respectively); 1 – diffusion boron–titanizing; 2 – diffusion titanizing; 3 – laser hardening.

The results of X-ray structural phase analysis show that during boron–titanizing, diffusion coatings consisting of complex borides of iron and titanium are formed in the proposed powder mixture. The main phase is the lower boride $(Fe,Ti)_2B$, which exhibits lower brittleness. The higher boride (Fe,Ti)B is present only in small amounts on the surface of ХВГ and ШХ15 steel samples. In ХВГ and ШХ15 steels, carbon displaced by boron appears in the form of Fe_3C carbides. As a result, carbon diffusion occurs in the intercrystalline regions, accompanied by the formation of Fe_3C carbides.

Measurements show that microhardness is distributed unevenly. In tests conducted on ХВГ, ШХ15, and Р18 steel samples, the maximum hardness values were 21 GPa, 18.6 GPa, and 17.6 GPa, respectively. These values were achieved at a diffusion layer thickness of 180 µm for ХВГ steel and 240 µm for ШХ15 and Р18 steels. The lowest hardness values were recorded at 11 GPa for ХВГ (480 µm), 10 GPa for ШХ15 (380 µm), and 8.8 GPa for Р18 (380 µm) (Figure 10). In the diffusion layer of ХВГ and ШХ15 steels, the titanium content increases up to 4%, while in other steels it rises to about 2%. The structural modification of the boride coating during boron–titanizing is most likely associated with the formation of new phases based on Fe_2B and FeB, namely $(Fe,Ti)_2B$, (Fe,Ti)B, $(Ti,Fe)_2B$, and (Ti,Fe)B.

Surface roughness varies depending on the laser processing speed. At an initial R_a = 2.7 µm, within the speed range of 10–18 mm/s, the surface quality deteriorates, and Rz increases up to 50 µm. As the speed increases, however, the indicators improve: at v = 30 mm/s, R_a reaches 1.25 µm and R_z decreases to 5.1 µm, which represents a significant improvement compared to the initial parameters.

Overall, laser processing with minimal melting significantly improves the wear resistance and antifriction properties of surfaces. This method provides a surface quality of $R_a = 1.25 \pm 0.63$ µm, making it suitable for use as a finishing treatment for certain components. The analysis results indicate that laser melting of a pre-polished surface considerably deteriorates its initial roughness, whereas processing without melting has a much smaller effect on the microgeometry. Subsequent polishing after laser treatment substantially improves the surface microgeometry (Figure 8).

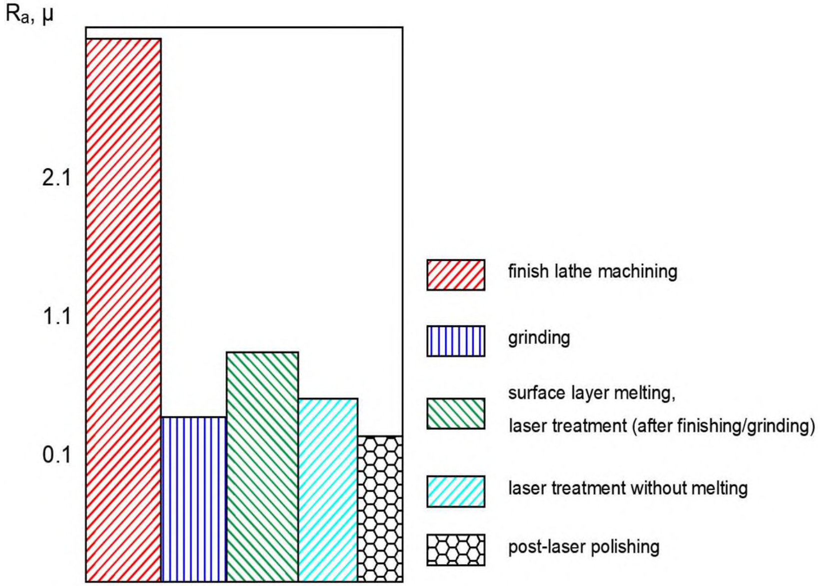


Figure 8. Variation of surface roughness of fuel pump precision components depending on the type of processing.

The processed areas consist of distinct zones differing in the degree of phase transformations. In the first zone, martensitic needles predominate, providing high wear resistance with a microhardness of 22.5 GPa. The second zone, following the “white layer,” consists of medium and fine needle-like martensite enriched with carbides, where the microhardness ranges between 12–14 GPa. The third zone corresponds to the initial state of the base metal, comprising fine-grained pearlite with a microhardness of 11.8 GPa. Between the laser-hardened zone and the base structural zone lies a transition zone approximately 50–80 µm wide, characterized by a microstructure of martensite, troostite, and granular pearlite regions.

Based on theoretical analysis and experimental data, dependencies were established for wear-resistant ХВГ steel showing the influence of the main laser irradiation parameters on the geometric dimensions of the laser-affected zone (Figure 9). These dependencies make it possible to determine the optimal regimes of laser processing in an efficient manner.

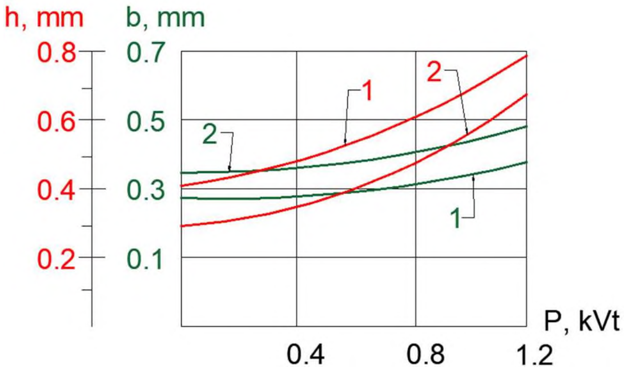


Figure 9. Dependence of the width (b, mm) and depth (h, mm) of the laser-affected zone in fuel pump precision components on irradiation power (V = 7 mm/s, d_n = 3 mm): 1 – ХВГ; 2 – ШХ15.

Studies conducted in the fourth chapter demonstrated that, as a result of laser processing of the tribological joints of fuel pumps, the geometric parameters, structure, and physico-mechanical properties of the layer vary depending on processing regimes, overlap coefficient, and beam parameters. This significantly increases wear resistance and, in some cases, ensures a self-healing effect of the surfaces. Both theoretical and experimental analyses confirmed that, compared to conventional methods, laser technology provides more precise control over layer quality, microgeometry, and durability indicators. When optimal regimes are selected, the reliability of precision components is substantially enhanced.

The fifth chapter addresses the following issues: the course of phase–structural transformations under laser influence; microhardness, residual stresses, and tribological characteristics of the hardened layer; the effect of the overlap coefficient on the formation of the layer structure and the selection of its optimal interval; the influence of the initial structure and heat treatment on the properties of the surface layer; and the impact of laser processing on roughness, geometric parameters, and microhardness distribution. Thus, the chapter develops a methodological basis for selecting laser regimes to enhance the reliability of precision joints.

The tribological properties of the laser-hardened layer were investigated. Tests showed that the highest wear resistance is achieved with the optimal arrangement of laser tracks (Figure 10), when the overlap coefficient falls within the interval k = (0.5–0.7)·d_f. At the initial stage of testing, waviness increases, and at subsequent stages it remains stable until the end of the tests. Moreover, the larger the spacing between the laser tracks, the greater the resulting waviness.

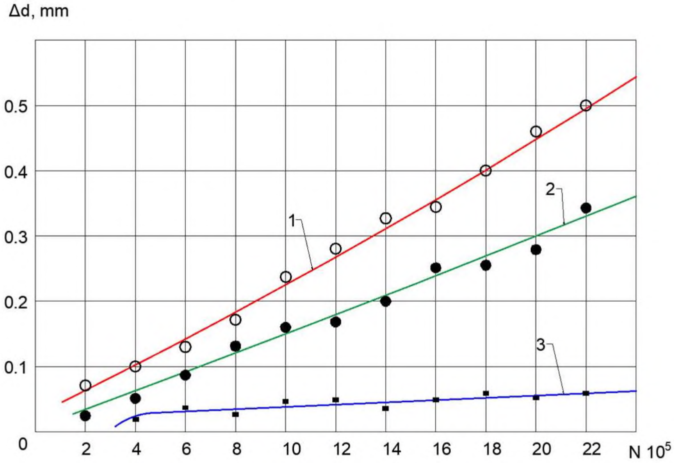


Figure 10. Variation of linear wear with the number of loading cycles in tests performed on a friction machine using the “roller–pad” scheme: 1 – strengthening with high-frequency current; 2 – laser processing with an overlap coefficient of k = 0.3·d_f; 3 – laser processing with an overlap coefficient of k = 0.5–0.7·d_f.

During laser surface hardening, as in other thermal hardening methods, an austenitic structure is formed in the heating stage and subsequently transforms into martensite during cooling. The transformation of pearlite into austenite, unlike in slow heating under isothermal conditions, occurs within the temperature range from Ac_1 to Ac_3 under a continuously increasing temperature regime.

To study the friction characteristics of the precision components of fuel pumps, tests were carried out under the following conditions: P = 700, d_n = 1.6 mm, v = 25 mm/s, and overlap coefficients K_n = 0.5;

0.75; 1; 1.25; 1.5; 2; 2.5; 3. It was found that in the friction pair with a bulk-hardened roller (Figure 11a), the testing process is characterized by a high friction moment and elevated temperatures of the contacting surfaces. However, when a laser-hardened roller is used, the testing process proceeds somewhat differently (Figure 11b). As a result, in the initial stage (40–50 minutes after the start of testing), the friction moment decreases sharply. The second stage of the testing process is characterized by a further reduction in the friction moment, which is associated with the wear of surface regions with lower hardness.

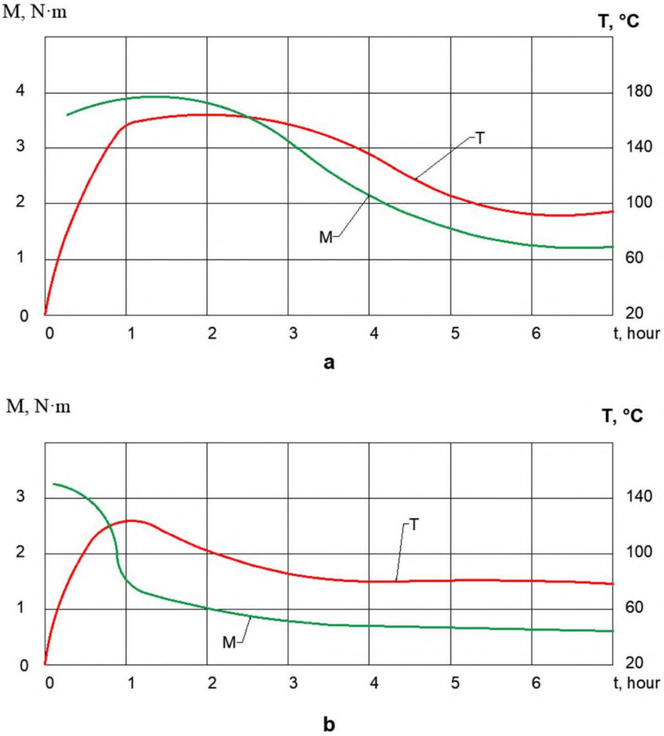


Figure 11. Dependence of the friction moment (M) and average surface temperature (T) of fuel pump precision parts on testing time (t): a — bulk-hardened roller; b — laser-hardened roller.

During laser hardening, when the overlap coefficient is $K_n = 2$, the average microhardness reaches 21.8 GPa but decreases to 12.4 GPa at the boundaries. Under conditions of $K_n = 1$, the second laser track leads to the formation of secondary zones in the previously processed area, where the microhardness first decreases to 11.8 GPa and then rises to 12.1 GPa. The optimal regime can be considered within the range of $K_n = 1.20–1.25$.

The analyses show that the regimes of laser thermal treatment in tribological joints operating under various friction and wear conditions play a decisive role in shaping the tribological properties of the surface layer and significantly enhance the antifriction behavior and wear resistance of precision components, particularly in the plunger and “plunger–pusher bolt” pairs. The structure and hardened surface layer formed by laser processing markedly increase resistance to failure and wear in the plunger and “plunger–pusher bolt” joints; thus, the selection of optimal laser regimes is substantiated as an effective approach to purposefully improving the reliability of precision joints.

CONCLUSIONS

1. Based on the study of the causes, characteristics, and types of wear occurring in the tribological joints of fuel pumps, it was determined that in order to reduce the intensity of abrasive, impact-abrasive, and mechanical wear and failure at the contact area of the plunger and “plunger–pusher bolt” caused by mechanical impurities in the fuel, it is necessary to form a reliable surface layer on precision components. This extends the operational limits of abrasive, impact-abrasive, and mechanical wear and creates the conditions for significantly increasing the reliability of precision components of fuel pumps [2, 3, 5].

2. It has been proven that conventional surface hardening methods of fuel pump precision components do not ensure the required physico-mechanical properties and reliability of tribological surfaces. As a result of theoretical and experimental research on solving the problem of improving the performance of fuel pump precision components, the application of laser surface hardening has been scientifically substantiated as the only effective method for hardening

the surfaces of tribological pairs in fuel pumps. The application of laser surface hardening has been justified for hardening the precision parts of fuel pumps (ХВГ, ШХ15, 25Х5МА, and Р18 steels) [4, 7, 14, 15].

3. The necessary analyses and studies were carried out to develop laser technology that ensures the formation of surface layers with high tribological properties on the surfaces of fuel pump precision joints [6, 11, 12].

4. The influence of laser processing regimes on the microgeometry of tribological joint surfaces has been studied. It was substantiated that laser processing technology can be applied as a finishing operation by forming surfaces with high tribological properties and a surface roughness of R_a = 0.63–1.25 μm [8, 10, 14].

5. Depending on the initial state of the material and operational parameters, the technological parameters of various wear-resistant laser treatments allow the experimental formation of layer structures with predetermined physico-mechanical properties [13 - 15].

6. A filling coefficient of the layer (K_c), which accounts for the degree of filling of the cross-section with solid phases and reflects its volumetric characteristics, and the overlap coefficient (K_n) were proposed. The selection of optimal overlap coefficients depending on the geometric parameters of laser tracks was presented [5, 9, 10].

7. For the parts of fuel pump tribological joints, the most efficient laser processing regime was determined as an overlap coefficient of K_n = 1.20–1.25, which ensures high wear resistance and antifriction properties of the surface, thereby guaranteeing reliability [5, 9, 10].

8. It is known that in the tribological joints of fuel pumps, the plunger is subject to abrasive and mechanical wear, while the "plunger–pusher bolt" pair is exposed to impact-abrasive wear. During laser treatment of these surfaces, maximum wear resistance was observed at overlap coefficients corresponding to the maximum values of the surface filling coefficient (K_c) [14, 15].

9. It was established that after laser surface hardening, the surface hardness of the tribological joints of fuel pumps increases 1.5–3.5 times compared to the hardness values of serially produced parts.

Moreover, laser surface hardening of precision components makes it possible to use them instead of rare, expensive, high-alloy tool steels by increasing the surface strength of available materials. Laser-hardened tribological pairs show high resistance to abrasive and impact-abrasive wear, while the friction coefficient of precision components is in the range of 0.10–0.11. Accelerated bench tests demonstrated that fuel pumps equipped with laser-hardened plungers and “plunger–pusher bolt” pairs possess approximately twice the service life compared to standard parts [1, 16].

10. The technological process developed for vacuum laser surface hardening of the precision components of fuel pump tribological joints was recommended for implementation in production by the “NeftQazMaş” plant. Calculations show that the application of laser surface hardening technology in a vacuum environment for precision components of fuel pumps provides significant economic benefits [1, 11, 16].

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The author's personal participation in published works

In works [1-4, 6, 7, 9, 12, 16], the author formulated the problem statement, proposed the solution method, and participated in verifying the correctness of the results.

In works [7, 8, 11, 13–15], the authors conducted the experiments and processed the results..

Works [5, 10] were performed independently by the author.

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