Improving the reliability of plunger pairs of diesel engines

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Abstract. Increasing the efficiency of diesel equipment operation is primarily associated not only with increasing the reliability of its main components, assemblies, joints and parts, but also with reducing costs and fuel consumption during production processes. At the same time, operating experience shows that a significant share of the operating time, the equipment is not fully loaded, often up to 40...50%. The transient and unsteady modes that arise in this case, as well as the design features of the fuel equipment of domestic diesel engines, lead to an excessive consumption of fuel and a significant increase in the unevenness of fuel supply through the engine cylinders to 26...38%. To ensure a minimum clearance in the plunger pair, it is proposed to apply a diamond-like thin film coating based on silicon oxycarbide onto the working surfaces of the parts, which has high microhardness, low friction coefficient, and prevents the setting of contact surfaces by finishing plasma hardening. After applying the technological operation of hardening the working surfaces of the parts by forming a thin film coating, the distribution of the parts over the time of crimping changed so that 82% of the experimental plunger pairs have a hydraulic density exceeding t = 45.7 s with an average value of t = 46.7 s with a mean square deviation σ = 1.05 s. The results obtained during the tests showed that at the nominal speed of rotation of the cam shaft, the cyclic feed of the produced plunger pairs decreased by 2.8%, while in the experimental ones, the decrease in fuel supply was 1.3%, the uneven fuel supply in both cases did not exceed 2%. The predicted resource of the experimental plunger pairs will be 9000 hours, which is 2.25 times more than the resource of serial plunger pairs.

1. Introduction
In modern economic conditions, agricultural enterprises are faced with the task of high-quality product manufacturing, of finding ways to reduce their cost. In the structure of production costs, a significant share (25%...30%) is fuel costs, which increase when energy-intensive soil cultivation processes are carried out.

Modern technologies for the manufacturing of crop products include a number of operational and technological processes: mechanical tillage, sowing and planting of various crops, the use of plant protection products, harvesting, transportation of products, etc.

Currently, the technological processes of tillage are characterized by agrotechnical, energy and economic indicators and the efficiency of agricultural machines and energy means is taken into account. At the same time, the means of mechanization available in agricultural enterprises require the solution of issues to improve the efficiency of their use.

The failure analysis of diesel agricultural machinery shows that more than 60% of all failures are related to the engine. Failures of diesel engines are associated with malfunction of the lubrication system of 7.6%, cooling system - 9.3%, power system - 39.8%, gas distribution mechanism - 3.9% and
others - 2.4%. The main reason for the failure of the diesel engine power supply system is associated with high-pressure fuel pumps (HPFP) - 60%, and also due to the wear of plunger pairs - 70%.

During operation of the fuel pumps, the moving mates of its parts, including plunger pairs, wear out. As a result of the wear of the fuel pump elements, there is a change in the size and shape of the parts, a change in roughness, mechanical properties and wear resistance, the formation of scoring, scratches, scrapes and other defects. The appearance of such defects is the reason for the deterioration of the technical condition of the high-pressure fuel pumps. Factors affecting the wear of plunger pairs of high-pressure fuel pumps can be classified by analogy with factors affecting the change in the technical condition of the product: structural, technological and operational.

Design factors are determined by the shapes and sizes of the parts, structural rigidity, the accuracy of the relative position of the surfaces and axes of the working parts, the correct choice of fittings, etc. Specific pressure on their surface, stress concentration, impact and fatigue strength of metal depend on the shapes and sizes of parts.

Structural rigidity is characterized by the property of parts, especially basic and fundamental, that are deformed slightly under the influence of perceived loads. The correct choice of fittings and the accuracy of the relative position of the parts ensures reliable operation of the mates.

Technological factors are those factors that depend on the quality of the materials used for the manufacture of parts, the use of appropriate heat treatment, assembly work (alignment, adjustment of gaps, quality of fastening, etc.), the qualifications of the worker, the level of technical equipment of the enterprise and the technological process, organization of labor, etc.

Operational factors depend on road and climatic conditions, on the type of technological operations performed, operating conditions, fuel quality, condition and quality of filter elements, etc. The mode of the diesel engine operation, which affects the load characteristic of the high-pressure fuel pump, depends on the type of technological operations performed.

The greatest influence on the technical condition of plunger pairs is exerted by operational factors, while structural and technological ones have an additional effect on the technical condition of parts.

Based on the classification of factors affecting the wear of plunger pairs, three types of reliability can be distinguished: constructive, production, and operational. Structural reliability is laid during the design of the product, production reliability is ensured during the production process, and operational reliability is manifested and ensured in operation.

The wear of the plunger pair parts is due to the mineral particles that make up the contaminants of the fuel. A study of the composition of mineral particles made it possible to establish that 90% of them consist of quartz and metal oxides (Al₂O₃, ZnO, etc.). The microhardness of such abrasive particles is quite high. So, the microhardness of aluminium oxide is 12000...13000 MPa, and that of quartz is 10300...11000 MPa, while the microhardness of the working surfaces of the plunger pair parts is only 9000...10500 MPa. Hence, the reason for the abrasive wear of plunger pair parts becomes apparent.

The presence of abrasive particles in the fuel, the ratio of their sizes to the gaps in the plunger pairs and the high speed of the fuel relative to the surface of the parts determine their hydroabrasive wear and abrasion due to the collision of particles and fuel with the surface of the plunger, as well as pinching of particles in the gap of the plunger-sleeve.

It is important to note that wear by particles pinched in the gap can occur in any area of the mating surfaces of the plunger pairs, and only those parts of the surfaces that come in contact with moving fuel can undergo hydroabrasive wear.

Improving the efficiency of diesel equipment operation is primarily associated not only with increasing the reliability of its main components, assemblies, joints and parts, but also with reducing costs and fuel consumption during production processes [1, 2]. Reducing fuel costs can be achieved in many ways, including various kinds of repair and restoration methods. The developed method for the restoration of precision parts [3], provides increased resource and reduced fuel consumption during the operation of plunger pairs of a high-pressure fuel pump (HPFP). But this method of increasing the durability of precision parts is advisable to apply during the repair of fuel equipment.
At the same time, operating experience shows that a significant share of the operating time, the equipment is not fully loaded, often up to 40...50% [4]. The transient and unsteady modes that arise in this case, as well as the design features of the fuel equipment of domestic diesel engines, lead to excessive consumption of fuel and a significant increase in the unevenness of fuel supply through the engine cylinders to 26...38% [5, 6]. Along with this, the wear rate of the main parts of the fuel equipment, especially precision, increases. Therefore, studies are aimed at improving the physico-mechanical and tribotechnical properties of the surface layers of the precision parts of fuel equipment, which can increase the efficiency of diesel technology.

2. Materials and methods
Currently, for the restoration and hardening of plunger pairs of high-pressure fuel pumps, there are a number of technologies based on the use of known methods, such as diffusion metallization, the use of filler materials, technologies for in-place surface restoration, electrospark alloying, technologies of plastic deformation of working surfaces and plasma. To ensure a minimum clearance in the plunger pair, it is proposed to apply a diamond-like thin film coating based on silicon oxycarbide onto the working surfaces of the parts, which has high microhardness, low friction coefficient, and prevents the setting of contact surfaces by finishing plasma hardening.

Given all the disadvantages of each method individually and the particular of the plunger pair wear, it is advisable to say that individually these methods do not provide wear resistance of the parts. We propose a combined technology for the restoration of plunger pairs, which allows increasing the efficiency of the restored parts. The method of electric spark recovery is the most promising among other methods, but since it has several disadvantages (formation of microcracks, peeling of the restored layer), it is necessary to apply additional technological operations to obtain the desired result.

The combined method of recovery and hardening of plunger pairs includes the following steps: the use of electric spark treatment, ultrasonic treatment and preservation of the resulting coating. These technical operations can be applied not only in combination, but also separately from each other. The proposed combined method is intended for plunger pairs that have fallen from a healthy state.

To improve the performance of plunger pairs and the fuel pump as a whole, it is proposed to strengthen the working surfaces of new precision parts by applying diamond-like thin film coatings.

Finishing plasma hardening (FPH) is a new technology for repeatedly increasing the working capacity of tools, dies, molds and machine parts, designed for mass application in industry. FPH is the final operation and is carried out after the final mechanical, thermal and abrasive processing of products. FPH are not subject to products that have traces of oxidation, burns, burrs, dullness, as well as oxide and organic coatings on hardened areas. The essence of FPH is the application of a wear-resistant coating with the simultaneous implementation of the process of re-plasma hardening of the subsurface layer. The coating is a product of plasma-chemical reactions of reagents that have passed through an arc plasmatron. Quenching occurs due to local exposure to a highly concentrated plasma jet. The effect of FPH is achieved by changing the physico-mechanical properties of the surface layer: increasing microhardness, reducing the coefficient of friction, creating compressive stresses, recovery microdefects.

3. Results
Incomplete engine loading and intermediate operating modes, which differ from the nominal ones, lead to a decrease in the speed of the HPFP plunger and increase the intensity of the flow of fuel into the annular gap.

The structural value of the gap in the plunger pair is estimated by hydraulic density and provides for their division into density groups. The performed analysis of the technical condition of the plunger pairs arriving as spare parts in terms of hydro-density showed that there is a sufficient reserve for increasing the efficiency of the fuel equipment of diesel equipment.

Hydraulic density studies were performed on manufactured, supplied as spare parts, and experimental plunger pairs. The experimental details were processed at the UVPU-111 device in laboratory of the training and research center "Restoration and hardening of machine parts" of the
department of technical service, standardization and metrology of Stavropol State Agrarian University. The results of the analysis are presented in Table 1 and Table 2.

### Table 1. The values of the differential and integral functions of the produced plunger pairs

| t    | 40.1…41.5 | 41.5…42.9 | 42.9…44.3 | 44.3…45.7 | 45.7…47.1 | 47.1…48.5 | 48.5…49.9 |
|------|------------|------------|------------|------------|------------|------------|------------|
| m_i | 11         | 15         | 10         | 7          | 2          | 3          | 2          |
| P_i | 0.22       | 0.30       | 0.20       | 0.14       | 0.04       | 0.06       | 0.04       |
| ∑P_i| 0.22       | 0.52       | 0.72       | 0.86       | 0.9        | 0.96       | 1          |
| f(t)| 0.25       | 0.28       | 0.21       | 0.13       | 0.07       | 0.03       | 0.02       |
| F(t)| 0.23       | 0.52       | 0.73       | 0.86       | 0.93       | 0.96       | 0.99       |

Analyzing Figure 1, it can be seen that 86% of the investigated produced plunger pairs have a crimping time not exceeding \( t = 45.7 \text{s} \), and the average value is 43.4s with a mean square deviation of \( \sigma = 2.29 \text{s} \). Such a distribution of plunger pairs indicates the possibility of increasing the resource and ensuring fuel supply stability at all operating modes by increasing the hydraulic density of precision parts and shifting the distribution center to the upper limit in the group. After applying the technological operation of hardening the working surfaces of the parts by forming a thin-film coating, the distribution of the parts over the time of crimping changed so that 82% of the experimental plunger pairs (Fig. 1) have a hydraulic density exceeding \( t = 45.7 \text{s} \) with an average value of 46.7s with a mean square deviation \( \sigma = 1.05 \text{s} \) [7].
The application of a thin film coating on the working surfaces of plunger pairs made it possible to increase the hydraulic density of all experimental parts. The crimping time of precision coated parts was more than $t = 45.1\text{s}$. At the same time, only 18% of the experimental plunger pairs have a hydraulic density less than $t = 45.7\text{s}$, while 86% of new pairs have this indicator up to this value. The data obtained during the experiment indicate an increase in the gap between the plunger and the sleeve for new parts that come as spare parts. The formation of a thin film coating on the working surfaces of new plunger pairs leads to an increase in hydraulic density, which indicates a decrease in the initial clearance in the plunger pairs.

When conducting comparative studies of the cyclic supply of the produced and experimental plunger pairs depending on the speed of the cam shaft of the fuel pump and the position of the rack, it was found that at a frequency of rotation of the cam shaft in the range of $200...1000 \text{min}^{-1}$ at $L=0\text{mm}$, which corresponds to the rack position of the maximum fuel supply, amounted to 115...45 ml or 26.1%, with $L=2\text{mm}$, $L=4\text{mm}$ and $L=6\text{mm}$, the decrease in cyclic supply was 57.1%, 54.5% and 53%, respectively [7].

Moreover, with the rack position $L=6\text{mm}$ in the range of the cam shaft rotation frequency of $200...300 \text{rpm}$, no fuel was supplied. Studies of the cyclic supply of experimental plunger pairs at different positions of the rack showed that when the rack position was $L=0\text{mm}$, there was no decrease
in fuel supply, at \( L = 2 \text{ mm}, L = 4 \text{ mm} \) and \( L = 6 \text{ mm} \), the decrease in cycle supply was 35.2%, 37.7% and 26.1%, respectively [7].

The results of the fuel supply unevenness study showed that the fuel supply unevenness of the produced plunger pairs, with rotation frequency a cam shaft of in the range of 200...1000 \( \text{min}^{-1} \) and a rack position of \( L = 0, L = 2 \text{ mm}, L = 4 \text{ mm} \) and \( L = 6 \text{ mm} \), is 25...36%, while in experimental cases it does not exceed 5% [7].

Comparative tests of 4UTNM HPFP plunger pairs were carried out at SDM 12-01 stand. The carried out studies made it possible to establish the dependence of the cyclic supply on the operating time and the rotation frequency of the cam shaft:

\[
q_{\text{cexp}} = 0.18 \cdot n - 0.0011 \cdot t - 9.05 \cdot 10^{-5} \cdot n^2 - 20.6
\]

\[
q_{\text{cser}} = 0.23 \cdot n - 0.0006 \cdot t - 0.0001 \cdot n^2 - 44.9
\]

where \( q_{\text{cexp}} \) and \( q_{\text{cser}} \) – respectively, the cyclic supply of experimental and serial plunger pairs, ml; \( t \) – operating time of plunger pairs, moto-h; \( n \) – the rotation frequency of the cam shaft of the fuel pump, \( \text{min}^{-1} \).

The results obtained during the tests showed that at the nominal rotation frequency of the cam shaft, the cyclic supply of the produced plunger pairs decreased by 2.8%, while in the experimental ones the decrease in fuel supply was 1.3%, the uneven fuel supply in both cases did not exceed 2% [7].

With a decrease in the rotation frequency of the cam shaft of the high-pressure fuel pumps to 800 \( \text{min}^{-1} \), the reduction in the cyclic supply of the experimental and factory plunger pairs was 1.8% and 5.5%, and the unevenness fuel supply in the sections increased to 2.3% and 6.7%, respectively [7].

At a rotation frequency of the cam shaft up to 500 \( \text{min}^{-1} \), the reduction in the cyclic supply of the experimental plunger pairs was 4.9% with a feed unevenness in sections of 2.8%, and in the factory 9.3% and 24.6%, respectively [7].

During the experiment, it was found that for serial and experimental plunger pairs, the wear rate is maximum at the maximum pressure in the contact zone and the maximum speed of relative displacement, therefore, the resource was calculated relative to these data. Based on the obtained calculations, a model for the formation of a gradual failure (Fig. 2) of serial and experimental plunger pairs is obtained [7].

![Figure 2. Model for the formation of gradual failure of serial and experimental plunger pairs.](image-url)
4. The discussion of the results
At the maximum pressure values in the contact zone and the relative displacement velocity, the process of the working surface wear of serial and experimental plunger pairs will occur at a speed of $\beta_{1s} = 9\mu m$ and $\beta_{1ex} = 0.85\mu m$ per 1000h, respectively. At such a wear rate, the predicted resource of serial plunger pairs will be $T_{min} = 2500h$, which is 2.4 times less than the experimental resource. At the minimum pressure values in the contact zone and the relative displacement velocity, the wear rate of the working surfaces of serial and experimental plunger pairs will be $\beta_{2s} = 5.5\mu m$ and $\beta_{2ex} = 0.57\mu m$ per 1000h, respectively. With such indicators, the resource of experimental plunger pairs will be $T_{max} = 9000h$, which is 2.25 times the resource of serial plunger pairs [7].

5. Results
Thus, the formation of wear-resistant thin film coatings on the working surfaces of plunger pairs provides not only an increase in resource of 2.25...2.4 times, but also an increase in the efficiency of diesel power facilities in the machine tractor unit by reducing fuel consumption by 15...17%.

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