

TECHNOLOGY FOR RESTORATION AND SURFACE HARDENING OF PLUNGER PAIRS IN HIGH-PRESSURE FUEL PUMPS

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Abstract. This article investigates the causes of wear in the plunger pairs of high-pressure fuel pumps (HPFP) of diesel engines during operation, as well as technologies for their restoration and surface hardness strengthening. In the course of the study, a comparative analysis of the effectiveness of traditional machining, galvanic chromium plating, and modern PVD (ion-plasma deposition) methods was conducted. The results indicate that applying a titanium nitride (TiN) coating to the plunger surface restores the hydraulic tightness of the micro-clearances and increases the service life of the part by 1.8–2.0 times. The recommendations presented in the article can be applied in maintenance and repair enterprises for automotive and agricultural machinery.

Keywords: high-pressure fuel pump, plunger pair, wear, restoration, strengthening, PVD coating, titanium nitride, micro-clearance, resource.

INTRODUCTION

Currently, on a global scale, improving the efficiency of internal combustion engines, particularly diesel engines, achieving fuel economy, and reducing the amount of harmful gases emitted into the atmosphere remain among the most urgent problems. The reliable and stable operation of diesel engines largely depends on the technical condition of its high-pressure fuel pumps (HPFP) and fuel injection equipment [1].

The most critical, heavily loaded, and high-precision component within the HPFP system is the plunger pair (comprising the plunger and the barrel/sleeve). The technological micro-clearance (gap) between the elements of this pair is extremely small, typically ranging between 1.5 and 2.5 μm . Maintaining this clearance with such precision enables the fuel to be pumped into the cylinders under a high pressure of 30 to 150 MPa (and higher) [2].

However, during operation, plunger pairs continuously function under extreme conditions. Their wear and subsequent failure are primarily driven by the following factors:

- Hydroabrasive wear: Microscopic solid particles and mechanical impurities present in the fuel entering the clearance under high pressure [3].
- Corrosion and cavitation: Degradation of the metal surface resulting from the presence of moisture (water) in the fuel and hydraulic shocks.
- Chemical wear: The utilization of low-quality fuel or fuel with a high sulfur content.

As a result of the wear on the plunger and sleeve surfaces, the clearance size expands beyond the permissible limit (exceeding 4–6 μm). This leads to fuel back-leakage, a drop in injection pressure, an increase in fuel consumption by up to 8–12%, and a significant reduction in engine power [4].

From economic and environmental perspectives, completely replacing worn-out plunger pairs with new ones is not always justified. Particularly, purchasing components for modern foreign machinery entails high expenditures. Therefore, extending the operational lifetime (resource) of worn plunger pairs by restoring their geometric dimensions and strengthening their working surfaces using innovative methods stands as an important scientific and practical task in modern mechanical engineering and repair manufacturing.

The aim of the research is to develop and evaluate the effectiveness of a technology to restore the worn surfaces of HPFP plunger pairs through mechanical and chemical-thermal treatment, and to enhance their service life (resource) by applying modern PVD nano-coatings.

METHODOLOGY

Within the scope of the study, the process of restoring and strengthening the working surfaces of HPFP plunger pairs was carried out according to a complex technological scheme. The experimental investigations comprised several sequential stages.

1. Defectoscopy and Surface Preparation

Initially, the technical condition and wear rate of the HPFP plunger pairs decommissioned from operation were analyzed. Geometric shape errors (ovality and taper) on the plunger and sleeve surfaces were determined using high-precision pneumatic length measuring instruments (passameters) and microscopes. During the machining stage, the internal surface of the sleeve was honed on special honing machines to eliminate micron-level irregularities, bringing its geometric shape to an ideal cylindrical state. The worn layer on the plunger surface was ground down to a depth of 4–6 μm [5].

2. Surface Strengthening Technologies

To restore the initial nominal dimensions of the plunger and to improve its resistance to abrasive wear, three different methods were applied and compared:

- Method A (Traditional thermal treatment): The component was carburized at a temperature of 930–950°C, followed by oil quenching and low-temperature tempering. This method served as the control variant.
- Method B (Galvanic chromium plating): A hard chromium layer with a thickness of 15–20 μm was deposited onto the plunger surface in an electrolytic bath (containing a solution of CrO_3 and H_2SO_4). Subsequently, the part was ground once more to achieve its final target dimensions.
- Method C (PVD ion-plasma deposition): The ground plungers were placed inside a vacuum chamber. The internal chamber pressure was evacuated to 10^{-3} Pa, and the surfaces of the parts were cleaned via ion bombardment. Then, at a temperature of 450–500°C within a nitrogen (N_2) atmosphere, an ultra-hard titanium nitride (TiN) nano-coating with a thickness of 2–4 μm was deposited onto the plunger surface via cathodic arc evaporation of a titanium (Ti) target [6].

3. Testing and Measurement Methodology

The quality of the restored and strengthened surfaces was evaluated based on the following performance parameters:

- Microhardness: Surface hardness (HV) was measured using a PMT-3 microhardness tester (Vickers method, under a 100 g load).
- Hydraulic tightness: The restored pairs were tested under high pressure using diesel fuel on a specialized KI-759 test bench, measuring the volume of fuel leaked per unit of time.

- Hydroabrasive wear test: Accelerated 100-hour laboratory tests of the plunger pairs were conducted in a fuel medium artificially mixed with 0.1% quartz particles.

RESULTS AND DISCUSSION

1. Surface Microhardness Analysis

The results obtained using the PMT-3 microhardness tester demonstrated that the surface strengthening method radically influences the mechanical properties of the component. While the traditional carburizing and quenching method (Method A) yielded a surface hardness in the range of 750–800 HV, galvanic chromium plating (Method B) increased this indicator to 950–1000 HV. The highest values were recorded in specimens subjected to the PVD method with a titanium nitride (TiN) nano-coating (Method C)—reaching 1800–2100 HV. This is approximately 2.5 times higher than the hardness of conventionally hardened metal. This outcome is explained by the formation of a highly dense nitride layer possessing a microcrystalline structure on the plunger surface.

2. Hydraulic Tightness and Resource Testing

Hydraulic tightness tests conducted on the KI-759 test bench confirmed that the quality of the clearance between the plunger and the sleeve was successfully restored. All restored components consistently maintained the initial operational injection pressure (30–40 MPa). As a result of the 100-hour accelerated wear tests in the abrasive-laden environment, the linear wear amounts (in microns) of the components were distributed as shown in Table 1.

Specimen Type / Method	Initial Clearance (μm)	Clearance after 100h (μm)	Wear Rate ($\mu\text{m/h}$)
Method A (Carburizing)	2.0	5.2	0.032
Method B (Galvanic Chrome)	2.0	3.8	0.018
Method C (PVD - TiN Coating)	2.0	2.6	0.006

As can be observed from the table, the wear rate of the plungers coated with PVD technology was 5.3 times lower compared to the traditional method, and 3 times lower compared to galvanic chromium plating.

3. Microstructure and Wear Mechanism Discussion

To understand the wear mechanism of the coatings, microscopic images of the plunger surfaces were examined. Due to the substantial thickness of the coating in the galvanic chromium plating method (15–20 μm), fine micro-cracks were observed under the microscope. These micro-cracks can lead to coating delamination (peeling) under fuel pressure during operation. Conversely, despite being ultra-thin (2–4 μm), the titanium nitride coating obtained via the PVD method bonds firmly with the base metal at the atomic level (high adhesion). No micro-cracks were detected in it, which completely blocks hydroabrasive particles from penetrating into the underlying metal.

CONCLUSION

- Wear Factors: It was determined that the primary cause of premature failure of HPFP plunger pairs is hydroabrasive wear occurring under the influence of microscopic mechanical impurities in the fuel, which alters the geometric dimensions of the micro-clearance (expanding beyond 4–6 μm).

- **Surface Hardness:** Applying a titanium nitride (TiN) nano-coating via the PVD (Physical Vapor Deposition) method enabled an increase in the microhardness of the plunger working surface up to 1800–2100 HV. This value is 2.5 times higher than that of the traditional carburizing-quenching method and 2 times higher than galvanic chromium plating.
- **Resource Extension:** Accelerated laboratory tests indicated that plungers with a titanium nitride coating exhibit the lowest wear rate (0.006 $\mu\text{m/h}$). This allows the operational resource of the restored plunger pairs to be increased by 1.8–2.0 times compared to brand new (factory) components.
- **Economic Efficiency:** Restoring plunger pairs using innovative vacuum-plasma deposition technology saves up to 40–50% of the cost of purchasing new components and serves to implement import-substituting technologies in transport enterprises.

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