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Finished plasma strengthening and restoration of fuel equipment details

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Abstract. The results of the investigation of the physical and mechanical properties of diamond-like coatings of the DLCPateks type (a-C: H / a-SiOCN) obtained on friction surfaces by transporting the atomic and molecular flux of vapor particles of liquid chemical compounds by a plasma jet of an arc plasma torch of atmospheric pressure are presented. The layer formed on the working surfaces is a non-metallic amorphous multilayer coating with a low coefficient of friction, increased microhardness, chemical inertness, hydrophilicity, high heat resistance and dielectric characteristics. To minimize the possible defectiveness of the main material, it is proposed to apply thin-film coatings to them at the final stage of manufacturing fuel equipment parts.

1. Introduction.
Recently, there has been a demand for technologies to strengthen and restore wear parts of fuel equipment for diesel engines that can extend their life, save financial, material and time costs of the consumer. In connection with this, the development of effective technologies for hardening and restoring fuel equipment parts is a promising direction of research [1 - 20]. This is also facilitated by the widespread use of machinery and equipment with foreign fuel equipment, for which the use of repair technologies is particularly economically justified.

One of the leaders in the diesel engine industry is the common rail injection fuel system manufactured by Bosch, Delphi, Denso, Siemens, etc. Almost every second diesel engine is equipped with such systems, therefore the development and research of technologies for the recovery of wear parts of this equipment is also actual task.

The main load on the parts that work under friction and wear conditions is perceived by a thin surface layer, and therefore wear resistant thin-film coatings are most often used. For a rational choice of coating materials and technologies for their application in order to increase the resource, reliability, and restoration of precision parts of fuel equipment, it is advisable to consider the conditions of their operation, the causes of wear and tear, to develop a methodology for choosing the optimal coating and the technology for applying it, and to investigate specific properties of coatings.

Coating technologies for hardening and restoring fuel equipment parts can be conditionally divided into three groups depending on the hardness of the created surface layer:
1. Hardness ≤ 5 GPa (less hardness of the base material):
- friction-mechanical brass; - alumochromophosphation; - ion-plasma spraying of the TiN-Cu-MoS₂ coating; - electrochemical-mechanical treatment using a renovation fluid in the form of a solution of polyethylene glycol with zinc; - electrospark deposition of copper-graphite coatings; - application of fluoroorganic surfactants (epilam);
- application of metal-ceramic coating from natural layered silicates on the basis of geoactivators (vermiculite, serpentine, etc.).

2. Hardness 5-8 GPa (of the order of hardness of the base material):
- electrolytic chromium plating; - diffusion chrome plating; - carbonitriding;
- electrolytic and gaseous chromium by thermal decomposition of chromium hexacarbonyl; - sulfochroming; - carbonitriding with the introduction of an activating coating.

3. Hardness ≥ 11-12 GPa (exceeding the hardness of abrasive particles):
- ion-plasma spraying of TiN coatings; - Electrolytic chromium plating with additional modification by ultradisperse diamonds;
- Electrolytic chromium plating with dielectric filler (aluminum oxide); - ion-plasma spraying of nanostructured TiN coatings; - coatings applied using physical (PVD) and chemical (CVD) vapor deposition coatings; - finishing plasma hardening with application of multi-layer wear-resistant coatings.

The technologies discussed above, as well as structural, technological and operational factors associated with wear resistance, have allowed us to formulate a methodology for selecting the optimal coating process for the purpose of hardening and restoring the details of fuel equipment. In accordance with the considered concept of choosing the technology for improving the durability of fuel equipment parts, we consider the final plasma hardening (FPH) with the application of a diamond-like coating DLCPateks (a-C: H / a-SiOCN). The FPH process is based on the decomposition of vapors of liquid chemical compounds introduced into the arc discharge plasma and the formation of an atomic and molecular particle flux in a plasma jet reactor. Heating of articles with FPH does not exceed 150 °C. As a result, a nonmetallic amorphous multilayer coating with low friction coefficient, increased microhardness, chemical inertness, hydrophilicity, high heat resistance and dielectric characteristics is formed on the working surfaces on the working surfaces.

The FPH also cleanses parts from process contaminants (microparticles, particles of processed and cutting material, metal oxides, components of lapping pastes, oil residues, solvents, fats, technological solutions, dust, sand, moisture, decomposition products of working and process fluids, microorganisms and products of their activities).

The analysis shows that about 80% of the plunger pairs initially have an increased clearance between the plunger and the bushing. Therefore, during the replacement of parts during the repair of fuel equipment, it is also advisable to produce their FPH with coating on the working surfaces of the DLCPateks coating, which will reduce the initial gap and will prevent the working surfaces from grasping.

2. Methods of conducting research.
When studying the properties of DLCPateks coated with FPH technology, the heat-treated steel ShKh15 was used as the substrate material. The thickness of the applied coating was of the order of 1 μm. To determine the coefficient of friction of the DLCPateks coating, the tests were carried out according to the “ball-disk” scheme using balls with a diameter of 3 mm made of silicon nitride Si₃N₄. The load on the counterbody was 5 N. The linear slip velocity was 10 cm/s. The friction path is 80-100 m. Nissan Oil SAE 5W-40 engine oil was used in the tests. Amorphous coating studies were carried out using a transmission electron microscope JEM 2100 (JEOL, Japan). To measure roughness parameters according to EN ISO 13565-2: 1996, the "Profile" measuring and computing complex was used. The adhesion of the DLCPateks coating to SHKH15 steel was determined by the scratch test method with the determination of the fracture initiation load at longitudinal displacement and its variable force on the diamond indentor.
3. The results of the research and their discussion.
Analysis of the results of nanoindentation revealed that with increasing load and, accordingly, with increasing contact depth, the hardness decreases, which characterizes the DLCPateks coating as gradient. Within one load, the hardness varies from 14 GPa to 23 GPa, which is typical of multicomponent coatings. The average properties of the DLCPateks coating: nanohardness is 18 GPa, Young's modulus is 127 GPa, elastic recovery is 87%. In Fig. 1 is a diagram of the indentation of DLCPateks coverage. The resistance of the surface layer to elastic deformation (plasticity index) of $H_{IT}/E_r$ is 0.14. The Young's modulus of SHX15 is 211 GPa. High value of plasticity index provides an increased life in the conditions of cyclic loads, and the proximity of the modulus of elasticity of the coating and the substrate contributes to the reduction of technological stresses on the interface and the increase of adhesive strength. In Fig. 2 is a diagram characterizing the decreasing character of the change in the coefficient of friction (lower curve) with the time of DLCPateks coating. The average value of the friction coefficient is 0.024.

![Fig. 1. F-h indentation diagrams for different loads of the DLCPateks coating (TI 750Ubi, Hysitron, USA)](image-url)
Fig. 2. Change in friction coefficient with coating time DLCPateks (TRB-S-DE, CSM-Instruments, Switzerland)

Studies with the JEM 2100 transmission electron microscope (JEOL, Japan) showed that the DLCPateks coating is amorphous (Figure 3) and represents a 60-100 Å structure. The amorphous (glassy) state of the coating material (in contrast to the crystalline state) is characterized by the absence of grain boundaries and dislocation defects, ensures the maximum effective filling of the cavities of the substrate profile.

Fig. 3. Electronogram of DLCPateks covering its amorphous character

Investigations of the contact angle of the raw steel SHKH15 without coating and coating for different liquid materials (Figure 4) showed that the DLCPateks coating provides more hydrophilic
properties of the surface (has a smaller angle of wetting). This leads to an increase in surface energy, which increases the wettability of the fuel and, accordingly, its lubricity.

![Figure 4](image1.png)

**Fig. 4.** The contact angle of wetting, where a) - is uncoated; b) - coated with DLCPateks (OCA 15EC, DataPhysics Instruments GmbH, Germany)

The adhesion of the coating DLCPateks to steel SHKH15 was determined by the method of scrap testing in accordance with ISO 20502: 2005. The measured load at which the depth of occurrence of the indenter in the composition "coating-substrate" ceases to grow smoothly, indicates the moment of destruction of the coating and characterizes its adhesion to the substrate. The loading of the DLCPateks coating with a thickness of 1.2 μm was 20 mN (Figure 5).

After coating with DLCPateks, the surface roughness parameters are improved. To measure roughness parameters according to EN ISO 13565-2: 1996, the "Profile" measuring and computing complex was used. When comparing the reference curves after the FPU, the parameter Rpk, which characterizes the height of the projections that wear out during run-in, decreased by 1.3 times; The parameter Rk, which characterizes the basis of the profile, decreased by 3.9 times.

Investigations of the three-dimensional surface topography using MarSurf WS1 from Mahr GmbH (Germany) transition zones DLCPateks coating SHKH15 steel backing also showed that after the coating is applied, the deep depressions of the surface relief are healed.

![Figure 5](image2.png)

**Fig. 5.** Three-dimensional surface relief and scratches, obtained by the scanning probe microscopy of the DLCPateks coating in determining the fracture load

When studying the electrical properties of the DLCPateks coating, its specific electrical resistance is determined, which is 106 Ohm · m. These dielectric characteristics of the coating should ensure the absence of electrochemical and electromechanical phenomena in friction.

Experimental bench tests to meet the tolerances of test plans have proved the possibility of using FPH technology with DLCPateks coating when restoring rod and multiplier valves, spray nozzles and Common Rail fuel injector valves. Currently, the plunger-type parts and the DLCPateks-coated prism are being tested at the UK MC "Altai Precision Products Plant" (Barnaul) on a non-motorized stand Hartridge Cri-PC.

4. Conclusions.

1. The most promising ways to harden and restore parts of fuel equipment are processes that exclude subsequent abrasive processing, for example, the FPH process with the application of a diamond-like coating of DLCPateks.
2. The effectiveness of the diamond-like coating of DLCPateks is determined by its amorphous state, hydrophilic properties, optimal physicomechanical, tribological and dielectric characteristics, the creation of compressive stresses on the surface, the reduction of roughness parameters, and increased adhesion.

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