Combined surface hardening of parts for friction pairs of gas turbine engines

D S Moeni Tabatabai, A G Boytsov*, V V Kuritsyna and S A Kazantsev

Institute of Aerospace High Technology and Production, Moscow Aviation Institute (National Research University), 4 Volokolamskoye shosse, Moscow 125993, Russia

*E-mail: tpdl@mail.ru

Abstract. The paper presents an analysis of the methods of surface hardening of parts. The authors experimentally worked out and determined the technology of combined hardening of parts of friction pairs of hydraulic pneumatic units, which allows increasing the efficiency and reliability of the units. In order to increase the life and reliability of precision friction pairs, the production feasibility of combining spark alloying and diamond smoothing has been substantiated. Technological and software for the formation of regular micro reliefs, surface reinforcement with combined processing are proposed.

1. Introduction
Statistics show that the largest number of malfunctions of fuel and hydraulic system units is associated with a malfunction of precision pairs and seal elements. Moreover, most failures, including failure of hydraulic units, occur due to the malfunctioning of control and distribution devices, as well as plunger, piston and plate pairs, which perform the functions of displacing or power elements of pumps and hydraulic motors.

The most common cause of increased friction, which causes jamming and failure of parts of slide control devices, is the setting of rubbing surfaces and fretting corrosion, which is a corrosion-abrasive process of destruction of the mating metal surfaces of parts subject to vibration.

The wear of the spool pair, caused most often by the delayed replacement of consumables (filters, and the hydraulic fluid itself) in the hydraulic dispersion mechanism, causes a decrease in pressure on the working body, which entails a decrease in the machine's working capacity, and a decrease in efficiency. Spontaneous movements or intermittent operation of the actuating mechanism of the servo hydraulic drive are caused by an increase in friction in the switchgear. Damage to the pumping pump assembly and the destruction of hydraulic motors are often the result of jamming of the plunger, plate or piston rotor pairs. In this regard, the analysis of the operating conditions and the establishment of the reasons for the failure of the precision pairs deserve special attention when developing measures to improve the reliability of hydraulic units.

Improving the reliability and service life of hydropneumatic units can be carried out by combined hardening, which will improve both the mechanical properties and the corrosion resistance of the working surfaces. To select the most suitable combined hardening method, it is necessary to analyze the operating conditions of hydropneumatic units, to determine the requirements for the quality of the surface layer.
2. Requirements for the quality of the surface layer
The main requirements for spool pairs are high stability of low friction forces and good tightness, i.e. the presence of minimal, not increasing during operation, above the permissible limit of leakage of the working fluid through the gaps between the parts.

In order to ensure minimum gaps in the pumping unit and at the same time to prevent jamming of parts and large wear of rubbing surfaces, stringent requirements are imposed on the geometric dimensions and cleanliness of the working surfaces of the parts of the plunger pumps. Plungers are made from cemented steels of tool and high-speed steels with hardness of working surfaces $HRA > 80$. Plunger blocks are made of alloy cast iron or special bronzes [1].

Clearance space the plunger into the cylinder is carried out with a permissible value between 0.015-0.02 mm, which is provided by pair selecting the plunger and the cylinder or lapping them. The surface roughness of the plungers is usually performed within the range of $Ra = 0.1...0.32$ microns. One of the main technical conditions is the requirement that the working surfaces of the plunger and cylinder are cylindricity; their roundness deviation and taper should not exceed 0.002 and 0.005 mm, respectively.

3. The choice of combined hardening method
For surface hardening, methods differing in nature of the hardening effect are used: surface plastic deformation (SPD), chemical heat treatment, highly concentrated energy flows (laser, electron beam, ion), coating of materials with high performance properties, etc. [2-4].

For various reasons, such as, for example, an increase in roughness, a decrease in the fatigue strength of adhesion of a coating to a substrate, the scope of many effective hardening processes is significantly limited. In such cases, by combining with another method of hardening (reducing roughness, increasing fatigue strength, decreasing porosity, and increasing adhesion strength), it is possible to achieve the required state of the surface layer and provide a high level of operational properties, expand technological capabilities [2, 5, 6].

Such combinations are called combined hardening [7]. By combining surface hardening methods, they also solve the problems of increasing the oil absorption of friction surfaces, hardening the substrate for the applied coating, and increasing accuracy. Combined hardening methods should be used for the most critical parts when traditional technology does not provide the required level of performance [8, 9].

The variety of hardening methods determines the breadth of possibilities for combining them. However, not all combinations are of practical value. In many cases, the technical indicators of the combined methods are similar. Some methods are incompatible, and their combination can lead to a decrease in the quality of the surface layer.

Based on the required characteristics of the surfaces of parts of friction pairs of hydropneumatic units, it is necessary, first of all, to provide resistance to fretting corrosion, and also to provide high antifriction properties. Electric spark doping makes it possible to significantly improve (by 2 … 10 times in comparison with the source material) such exploitation characteristics of parts as abrasion resistance, fretting resistance, hardness, surface strength, temperature constancy. Therefore, the first step in combined hardening should be the selection of spark alloying. Reinforcing the surfaces of parts of friction pairs of hydropneumatic units with a bronze alloying electrode makes it possible to obtain alloyed sections providing antifriction, and wear resistance is determined by the main material.

At the second stage of combined hardening, the surface is diamond-smoothed, resulting in increased surface hardness.

4. Electrospark alloy surface reinforcement
With electrospark alloying, the formation of a hardened layer is achieved by transferring the material of the alloying electrode (anode) to the hardened product (cathode) during electrical impulse discharges [10, 11]. Particles of the alloyed electrode materials melted by an electric spark discharge and the parts are mixed and deposited on the hardened surface, forming a layer of alloy saturated with elements and quenched to high hardness (more than 82 HRA up to 90 HRA). The microhardness of the surface of the parts is reached by the value of 16000 … 20000 MPa at the depth of the hardened layer up to 400 microns.
Hard alloys (VK6, T15K6, etc.), carbides, nitrides and borides of transition metals are used as alloying electrodes (TiC, WC, TiB$_2$, NbC, CrC, ZrB$_2$, etc.), metals (Ti, Cr, Co, Ni, Al, W, Mo, Re, Ta, Hf, etc.), as well as alloys based on them.

The required value of the interelectrode gap is supported by the movement of the electromechanical tracking system (U). In order to increase the flatness of the hardened layer and uniform erosion of the alloying electrode, it is given rotation from an electric motor with a frequency of 400 ... 4000 rpm. The alloying electrode with a diameter of 0.5 ... 2.0 mm is installed in a collet chuck.

The alloying process scheme is shown in figure 1. Alloy electrode (1) is an anode, and hardened product (2), installed on the desktop (3), the cathode. The parameters of electric spark discharges are selected so that predominant erosion of the alloying electrode occurs. The necessary power, frequency and duration of the discharges are provided by a pulse generator, which supplies rectangular voltage pulses to the doping electrode.

![Figure 1. Electrosparl alloying process scheme: (1) alloy electrode; (2) hardenable product; (3) platten; (4) application head; (5) servomotor of tracking system; (6) gearbox; (7) feed-screw.](image)

The required value of the interelectrode gap is supported by an electromechanical servo system, by moving the servo head (4) in the vertical direction by means of an actuator motor (5), a worm gearbox (6) and a lead screw (7). The engine (5) is controlled by a servo unit.

The performance of alloying is determined by the speed of movement of the alloying electrode relative to the hardened surface. The equipment for Electrical Discharge Machining (EDM) “ELFA-731” provides the movement of the alloying electrode along the coordinates X, Y, Z (figure 2).

“ELFA-731” machine is equipped with a CNC system “Fanuc-3M”. This CNC device is focused on manual input of control information in a dialogue mode. Due to this, it is possible to prepare a control program directly at the machine, based on the drawing data.

Surface reinforcement consists in hardening local areas evenly spaced on the surface. Such processing can provide the necessary level of operational properties with a significant increase in productivity. In addition, surface reinforcement allows you to combine the properties of the base material and the material of the hardened sections.
Figure 2. Working zone of electric-discharge milling system: (1) gantry; (2) support; (3) head; (4) pulse generators; (5) bath.

The geometric shape of the hardened sections can be very different. It is important that it ensures the uniformity (regularity) of the distribution of plots on the surface. Some possible site shapes are shown on the figure 3. The choice of form depends on the capabilities of the used CNC equipment.

Other things being equal, the operational properties of reinforced surfaces depend on the ratio of hardened ($S_{H}$) and not hardened ($S_{0}$) areas ($bp$), as well as relief density ($D_{R}$), that is, the number of cells per surface unit (per sq.cm).

When surface reinforcing on CNC equipment, for example, the “ELFA-731” machine, it is advisable to apply cells in a hexagonal or square shape (figure 3a and 3b). In these cases, the specified parameters are calculated by the formulas (1) for hexagonal cells, and (2) for square cells:

$$bp_{6} = \frac{S_{H}}{S_{0}} = \frac{a_{6}^{2}}{(a_{6} - \frac{d_{e}}{\sqrt{3}})^{2}} - 1, \quad D_{R6} = \frac{200}{3\sqrt{3}a_{6}^{2}},$$  \hspace{1cm} (1)

$$bp_{4} = \frac{a_{4}^{2}}{(a_{4} - d_{e})^{2}} - 1, \quad D_{R4} = \frac{100}{a_{4}^{2}},$$  \hspace{1cm} (2)

where $d_{e}$ – diameter of alloying electrode; $a$ – side of a hexagon or square (cell parameter); indexes (4) and (6) refer to a square or hexagon, respectively.

It is also advisable to apply a relief in the form of circular sections having an electrode diameter by periodically stopping the alloying electrode for periods of time during which the area under the electrode is alloyed. It is desirable to arrange the hardened round sections in the corners of the square (figure 3c).
Figure 3. Forms of hardened areas used in surface reinforcement.

The relief density indicators are calculated using the following formulas:

\[ b_{pa} = \frac{\pi d_a^2}{d_a^2 - \pi d_e^2} \], \quad D_{ra} = \frac{100}{d_a^2}, \quad (3) \]

or ensure their tight packing (figure 3 d), then the calculation of the relief density indices is performed according to the formulas:

\[ b_{pe} = \frac{\pi d_e^2}{\frac{\sqrt{3}}{2} d_e^2 - \pi d_e^2} \], \quad D_{re} = \frac{200}{9 \sqrt{3} d_e^2}. \quad (4) \]

The advantage of such a reinforcement technology is the possibility of obtaining a greater relief density at the same values \( bp \) [12].

Surface reinforcement can be combined with unbroken spark alloying. For example, first a layer is applied with an alloying electrode of wear-resistant material, and then a relief of antifriction material is formed [13]. It is also obvious that it is possible to cross-apply reliefs shifted relative to each other by a certain amount, with the selection of the sizes of square or rectangular cells and the magnitude of the shift, providing hardening of the entire surface, and it will consist of sections hardened with various materials. For example, first a grid of cells is alloyed with a wear-resistant material, and then, with a shift, a grid of cells of anti-friction material is applied. The possibilities here are very wide. Figure 4 shows a photograph of a part with a surface treated by this technology.

Figure 4. BK6-M coating, on top bronze.

Since grooves or grooves are formed during such processing, if there are requirements for the tightness of the mating parts, it is recommended to apply the relief in the form of a closed mesh with
hexagonal or other cells. On the contrary, in order to improve the flow of oil in the contact surfaces, it is advisable to apply reliefs of the open type (figures 3e and 3f).

5. Diamond smoothing as a means of forming a regular microrelief

The next stage of combined hardening is diamond smoothing. By combining surface reinforcement and diamond smoothing, it is possible to obtain reinforced regular microreliefs, i.e. surfaces with protrusions made of hardened material [14, 15].

Due to the greater hardness of the hardened sections, the depth of the smoothing agent on the initial (not hardened) material is greater than on the hardened one. Respectively, the plastic displacement of the material is also large. As a result, after ironing, a regular microrelief is formed, the protrusions of which are made of a material of higher hardness (up to 90 HRA) hardened by electrospark alloying, than other sections (about 75 HRA) (figure 5).

The maximum possible depth of the microrelief formed after smoothing ($R_{\text{max}}$) can be determined from the dependence:

$$R_{\text{max}} = h_0 - h_H + \Delta h = h_0 (1 - \frac{H_0}{H_H}) + \Delta h,$$

where $h_0$ and $h_H$ – the smoothing depths when smoothing the initial and hardened areas, respectively; $\Delta h$ – the difference between the levels of the original and hardened electrodischarge hardening of surfaces; $H_0$ and $H_H$ – hardness of the initial and hardened sections, respectively.

The microrelief depth increases with a decrease in the smoothing radius $R_{sf}$:

$$R_{\text{max}} = R'_{\text{max}} \frac{1}{R_{sf}},$$

where $R'_{\text{max}}$ – microrelief depth when machining with a radius smoother $R_{sf}=1$ mm.

Due to the mutual influence of hardened areas, with their close proximity, the depth of the regular microrelief decreases with a decrease in the length of the initial sections, and its determination must be carried out experimentally.

Figure 6 shows photographs of parts treated with surface reinforcement.

**Figure 5.** The scheme of formation of the hardened microrelief.  
**Figure 6.** Parts hardened by electrodischarge hardening and smoothing.

Figures 7 and 8 show a technological scheme and an algorithm for a flexible control program, which is advisable to use for applying regular microreliefs in the form of a set of hexagonal cells with side $a$ ($a_z$) on flat surfaces bounded by a rectangle with dimensions of sides ($B$) and ($L$), or surfaces of revolution with a diameter ($D$) and length ($B$).
Figure 7. Operational design of a hexagonal microrelief formation program.

Figure 8. The algorithm of the control program for the formation of the hexagonal relief.
The method of forming regular microreliefs proposed in the work by combined processing based on electroerosive hardening followed by diamond smoothing is expediently used to harden the surfaces of friction pairs of hydropneumatic units. By means of electroerosive hardening, sections regularly located on the surface are hardened, and after diamond smoothing, due to differences in hardness of the hardened and initial sections, protrusions are formed from the material hardened by electroerosive hardening.

The obtained analytical expressions allow us to calculate the height of the microrelief. The developed method of combined hardening allows to improve the lubrication conditions of the surfaces of friction pairs, to optimally combine the properties of the base and alloyed materials.

An express assessment of the wear resistance of surfaces treated with the combined hardening technology was carried out under the conditions of reciprocating movements with the counterbody of the test samples and witness samples. The methods of experimental rapid assessment and data processing are of a special nature and allow you to perform a comparative analysis in terms of wear resistance, bearing capacity, fatigue resistance and other tribotechnical indicators [16]. Tests of samples with a surface-reinforced layer of combined hardening under various loading conditions showed a decrease in the friction coefficient up to ten times, a multiple increase in wear resistance and resistance to fretting corrosion damage.

An assessment of the production feasibility and industrial potential of research and development in the field of hardening and restoration of parts for aircraft gas turbine engines and assemblies [17-19] shows, that electric spark alloying and combined methods based on it are an effective tool to ensure the service properties of a wide range of aircraft products.

6. Conclusion
A new technology of combined hardening is proposed, based on the combination of electroerosive hardening and diamond smoothing with the creation of the effect of surface reinforcement and the creation of special regular microreliefs. Diamond smoothing is the most suitable method of surface plastic deformation for processing surfaces hardened by electric spark alloying. This is due to the high hardness of the diamond and the specific conditions of its contact interaction with the alloyed layer, which achieves plastic deformation of the hardest deposited materials. A combination of surface reinforcement and diamond smoothing can produce reinforced regular microreliefs, i.e. surfaces with protrusions made of hardened material. The advantages of these developments in comparison with the known ones are: locality of hardening, high adhesion strength of the coating to the substrate, the ability to actively control the composition, properties and microgeometry of the surface layer.

The proposed technology of combined surface hardening, based on a combination of electrospark alloying processes in the form of local reinforcement and diamond smoothing, was applied on the details of the rods of plunger pairs of hydraulic units. The proposed technological solutions, software methods and means of implementing the process made it possible to meet the requirements for accuracy and micro geometry of the working surface with a significant increase in the life of a friction pair under conditions of hydrodynamic lubrication. Completed investigation of the operational properties of parts of pneumatic units showed the high efficiency of combined hardening to ensure the service characteristics and service life of machines, devices and assemblies.

Thus, combined hardening with the formation of regular microreliefs makes it possible to increase the life of pneumatic hydraulic units by an order of magnitude without making any design changes to the geometry of the part.

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