CHALLENGES OF PROPERTY INHERITANCE DURING THE TECHNOLOGICAL PROCESSING OF FUEL PUMP PRECISION PARTS

Alakbar Huseynov[1], Ilgar Nazarov[2], Farid Huseynli[3*], Mirzabay Safarov[4]

[1]Azerbaijan Technical University, Baku, Azerbaijan; h_alakbar@aztu.edu.az; ORCiD 0009-0005-5299-1103

[2]Azersilah Holding, Baku, Azerbaijan; ilqar.nezerov@mail.ru

[3]Azerbaijan Technical University, Baku, Azerbaijan; ORCiD 0009-0007-5393-9440

[4]National Aerospace Agency, Baku, Azerbaijan; ali.rahman.7534@gmail.com

*Corresponding author: farid.huseynli@aztu.edu.az , mob: +994509614725

ABSTRACT

Laser surface hardening technology is a progressive innovation compared to traditional processing methods. The maximum hardening effect from laser surface treatment is achieved in combined technology, where the laser thermal treatment is preceded by a paste treatment or a coating application operation. With the discrete laser coating method of surface coatings, it is possible to create surfaces of certain shapes, sizes and properties on the surface, which will ensure the hardness, wear resistance and reliability of the surface during the friction process. During boronchromization, the following primary materials for powder mixtures were used: Х97 ГОСТ 5905-79 chromium powder with a fraction of 0.07...0.2 mm; В4С3Н ТУ2-036-879-81 boron carbide polishing powder, ПЦ-2 ГОСТ 12601-76 zinc powder, Al2O3 GOST 3136-76 aluminum oxide. The complex diffusion metallization method chosen for the restoration of worn precision parts of fuel apparatus and pumps allows not only to restore linear dimensions, but also to harden the restored surfaces. Laser heating, which causes phase changes in the surface layer, requires a minimum density of radiation energy (103 - 104 W/cm²) and an exposure time of 10-3 - 10-2 s. It is possible to harden and restore the surface by applying paste to precision parts and then using the diffusion metallization method in vacuum with a laser.

Keywords: pasta, diffusion metallization, laser, complex boronchromization, surface hardness, roughness

1. Introduction

The surfaces of the friction pairs of the plunger and the barrel, which are precision parts of fuel pumps, operate under conditions of high temperatures and aggressive environments, and at this time they are subjected to cyclic, alternating and shock loads. During friction between pairs, the internal layers of machine parts are subjected to deformation, re-deformation, oxidation and abrasive wear, corrosion, and breakdown from various internal and external influences [1, 2].

Surface hardness and geometric characteristics are the main factors determining its wear resistance of processing parts of fuel pumps. Therefore, special attention is paid to the surface before use. Surface treatment is an integral part of the technological process of hardening machine parts, equipment and working tools, which allows to increase their durability and wear resistance by 2-5 times. Traditional hardening methods are widely used to increase wear resistance: application of composite coatings by plasma-arc methods, mechanical surface treatment methods, heat and chemical-heat treatments [3, 4].

Recently, laser technology and surface heat treatment technologies have seen rapid development. High-speed local laser heating and subsequent rapid cooling throughout the volume of the material allow obtaining a uniformly distributed structure, which provides a wide range of properties, as well as a complex of inheritance properties of technological processes which is microstructural memory, phase stability, persistence of surface properties and so on. After laser processing, there is a no mechanical impact and deformation of the processed plunger pairs during operation, which creates conditions for easy automation and application of equipment. Laser surface hardening technology is progressive and innovative compared to traditional processing methods. However, the issues of heredity of the parameters of laser surface treatment modes during processing are focused on studying the laws of interaction of laser radiation with structural materials and alloyed steels. It is relevant to study the hardening and restoration of the surface with laser radiation after vacuum diffusion metallization of fuel pump plunger pairs after paste processing, vacuum diffusion chromium plating, titanization and complex boron chromium plating

The maximum hardening effect of laser surface treatment is achieved in combined technology, where the laser thermal

treatment is preceded by a paste treatment and followed by a coating application operation. Composite wear-resistant coatings on austenitic (Fe-Cr-Ni, Fe-Mn) and austenitic-martensitic matrix carbide compounds have shown positive results during the lifespan, taking into account the share of processing during mechanical loading of precision parts. The main feature of these materials is the ability of austenite to transform into martensite during the friction process, which increases their wear resistance. The hardness of the surface coating varies in the range of 17 - 18 GPa.

Purpose of the work. Heritage issues in the process of surface hardness enhancement and restoration of precision parts of fuel pumps using laser-assisted diffusion chromizing, titanizing, and complex boron-chromizing under vacuum with paste application.

Subject of research: In this study, three steel grades (ХВГ, ШХ15, and Р18) were coated using both galvanic and diffusion metallization techniques. The impact of coating method on surface roughness, microhardness, and porosity was investigated. Laser-assisted diffusion processes under vacuum conditions were also explored to evaluate their effectiveness in restoring the wear resistance of precision plunger-barrel pairs.

2. Materials and Methods

Objects and materials of the study: The Unified Fuel Pump and Diesel Pump -type fuel pumps consist of pairs made from alloyed steels such as AISI L2 (ХВГ), AISI 52100 (ШХ15), and AISI M2 (Р18).

Equipment used to increase the surface hardening of precision parts with a vacuum laser - a vacuum laser diffusion metallization device patented by the authors was used in the "Diffusion metallization and Technology of Special Purpose Products" laboratory of the Azerbaijan Technical University to increase the surface strength of the material. (Figure 1).

Figure 1. Vacuum laser diffusion metallization device.

To assess the roughness of the cleaned surface, a profilograph-profilometer model 253 was used (Fig. 3). The roughness of the surface is determined by the parameters Ra and Rz in accordance with ГОСT 2789-73. The deviation of

the device is 10%. The arithmetic mean deviation of the Ra profile was determined according to the readings of the device, the height of the Ra and Rz errors according to the profilogram recorded on the device. The measurement was carried out on at least six parts of each sample. The true value of the Ra and Rz values is taken on the basis of the arithmetic mean and maximum values of the six measurements. The speed of movement of the sensor with a diamond head was 0.1 mm/min. The profilogram recording was magnified vertically from 2000 to 200,000 times and horizontally from 20 to 80 times on ЗТЬ - I electrical-hermetic paper.
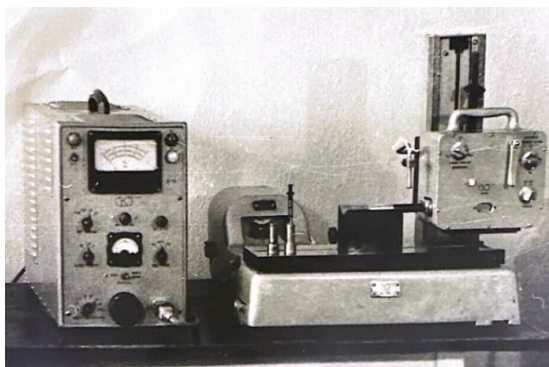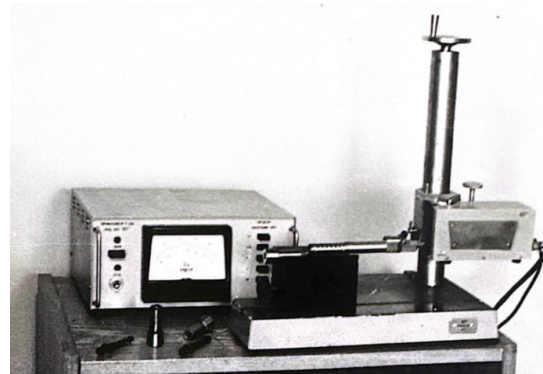

Figure 2. Profilograph-profilometer 253 measuring device.

The plungers were measured using an "ОГП" opticometer— a precision optical instrument designed for non-contact measurement of cylindrical parts. This device enables accurate assessment of parameters such as diameter, roundness, and surface quality, which is essential for evaluating the effects of surface treatment processes. The plungers were measured on an "ОГП" opticometer with a division of 0.0002 mm. The plunger barrel was measured with an E-2I ratiometer with a division of 0.00025 mm. The taper and roundness of the barrel were evaluated using an E-92IA ratometer, a high-precision instrument designed to assess deviations from circularity and axial symmetry. This device allows for accurate measurement of taper angles and roundness deviations, providing critical data on the geometric accuracy of cylindrical components after surface treatment. The taper and roundness of the barrel were evaluated on an E-92IA ratometer, and appropriate templates used at the "Iqlim Scientific-Production Enterprise" were used. The taper, roundness, cylindrical shape of the plunger and selected groups were determined

using an "0П286" type opticometer. The wear rate of the plunger pairs was determined by micro-measurements on the indicated devices. The plunger and barrel were measured in five sections and in two mutually perpendicular planes according to the micrometer cards of the manufacturer.

In combination with measuring devices, the pneumatic "dilinometer - rotameter" allows you to measure practically all parameters of precision parts of fuel pumps: ovality, conicity, mutual arrangement of surfaces, etc. (Figure 3).
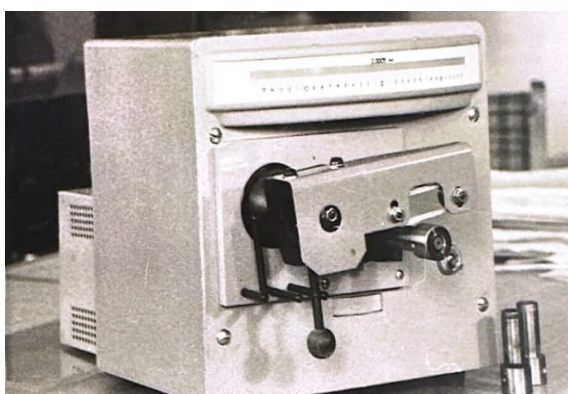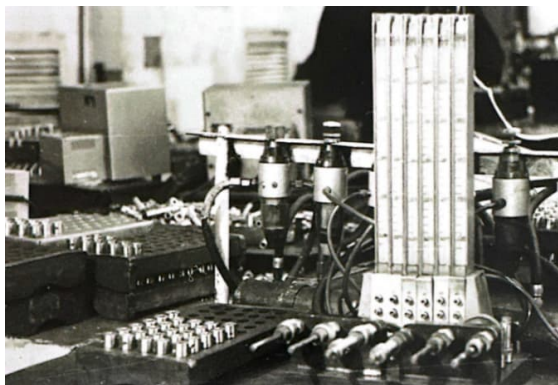

Figure 3. Determination of the geometric dimensions of plungers and barrels - "dilinometer - ratiometer".

Devices for measuring precision parts of the fuel apparatus are described (Figures 5, 6, 7).
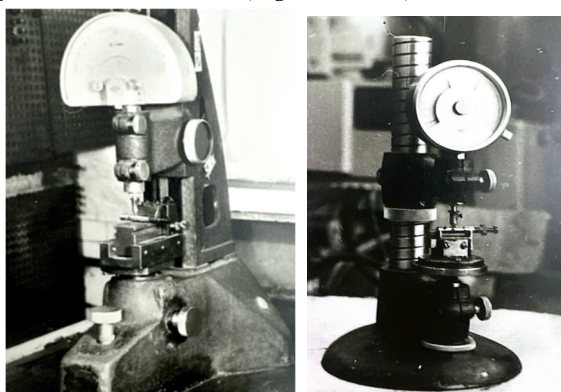

Figure 3. Instruments for measuring the dimensions of the barrel and plunger.

The optical hardness measurement method was used for metallographic research. For this purpose, the measuring devices shown in Figure 4 were used. The surface microhardness of the samples was determined according to Vickers, and the hardness was determined according to Rockwell and Brinell (Figure 4).

Determination of the hardness and microhardness of the parts was measured using the measuring devices shown in Figure 4: "TKC-1M" and "ПMT-3M".

In accordance with ГОСТ 9013-59 (CMEA standard 469-77), hardness testing was carried out on the "TKS-IM" hardness tester by the Rockwell method. Hardness was measured by pressing a diamond cone with a vertex angle of 120° onto the applied surface under a load of 150 N and 300 N. Hardness was determined based on the readings on the "d" scale of the TKS-1M tester. Tables were used to convert the obtained values to HRC.

Microhardness measurements were carried out in accordance with ГОСТ 9450-76 (standard SEB I95-78) with Vickers Hμ on the "ПMT-3M" device according to the Vickers parameter. The tests were carried out using a diamond pyramid with a vertex angle of 136° under a load of 0.98 N. The microhardness value was determined from the "trace diagonal – microhardness" table compiled after the calibration of the device.

a)

b)

Figure 4. Devices used to determine the microhardness and hardness of parts ("ПMT -3M" – a, "TKC – 1M" and "Buehler" - b).

The surface hardening process involved an initial step of applying a paste containing the desired elements (chromium, titanium, and boron for complex borochromizing) onto the precision parts. Following the paste application, the parts were placed in a vacuum chamber (CHB-1.3.1 /16). To facilitate the diffusion of these elements into the steel substrate, a laser system, integrated into the vacuum chamber, was employed to irradiate the coated surfaces. The laser irradiation parameters, including power, scanning speed, irradiation time were carefully controlled to promote efficient diffusion without causing surface damage. Subsequently, a controlled cooling cycle was implemented.

Steel grade	C	Mn	Cr	Ni	Mo	W	Y	Co	Ti	Cu	Si	P	S
ХВГ	0,90-1,05	0,80-1,10	0,90-1,20	0,0035	0.30	1.20-1.60	0.05	-	0.03	0.3	0,15-0,35	0,030	0,03
ШХ15	0,95-1,00	0,20-0,40	1,30-1,65	0.30	-	-	-	-	-	0.25	0,17-0,37	0,027	0,02
Р18	0,70-0,80	0,4	3,8-4,4	0.35	1.0	17,0-18,5	1,0-1,4	0.6	-	0.45	-	0,030	0,03

Table 1. Chemical composition of steels subjected to complex diffusion metallization

So far, no research has been conducted on the diffusion recovery and increase of surface hardness of precision parts of machines and equipment by pre-coating with paste, chromium plating, titanization and complex boronchromization in vacuum [5-9].

The complex surface hardening process has not been sufficiently studied. It is practically impossible to predict its course for a specific steel grade. In this regard, experimental data are of certain practical interest.

The aim of these consecutive studies is to study the possibility of restoring and strengthening precision parts of the fuel assembly using the method of complex diffusion metallization, alloyed titanization and borochromization.

To increase the thickness of the diffusion layer, the surface of the samples was simultaneously saturated with metal (chromium, titanium) and non-metal (boron). Chromium plating, titanization and boronchromium plating were carried out in vacuum in CHB-1.3.1 /16 device which shown in figure 1, with protection from the atmospheric environment.

Samples of steels ХВГ, ШХ15, Р18 used in the production of precision parts of machines and equipment were studied. The selection of steel grades was carried out in order to study the degree of influence of alloying elements on the thickness of the obtained diffusion layer and the increase in the linear dimensions of the details (table 1).

The steels ХВГ, ШХ15, and Р18 were tested in this study by applying both galvanic and diffusion coatings. n galvanic coating, a metallic chromium layer was electrochemically deposited under controlled current density and temperature. In contrast, diffusion coatings were applied using vacuum-based laser diffusion metallization after paste application.

The recovered parts and samples were packed in cylindrical containers. The distance from the walls of the container to the part was at least 10 mm, and between the parts was 5-8 mm. The top of the container was insulated with an asbestos interlayer and a fused lid made of nitrosilicate clay and liquid glass.

During borochromization, the initial materials for powder mixtures were chromium powder Х97 ГОСТ 5905-79 with a fraction of 0.07...0.2 mm; polishing powder from boron carbide В4С3Н ТУ2-036-879-81, zinc powder ПЦ-2 ГОСТ 12601-76, aluminum oxide Al2O3 ГОСТ 3136-76. Borax NaB407 ГОСТ 4199-76 and potassium fluoride КР ГОСТ 20348-75 were used as process activators. Before mixing, chromium and boron carbide powders were dried at 300°C for 3 hours, aluminum oxide was calcined at 700°C for 3 hours; borax and potassium fluoride were dried at 200°C for 2 hours. Conducted on CHB-1.3.1 /16 device.

After drying, the powders were carefully mixed, observing the percentages in the mixture. The finished mixture was stored in a hermetic container. The operating temperature of the process was set by means of a regulating millivoltmeter in the control unit of the CHB-1.3.1 /16 device. The time for the device to reach a temperature of 950-1050 °C was 1.1±0.1 hours. The duration of holding in the saturation mode was controlled by a clock, while the operating temperature in the device chamber was automatically maintained by a thyristor regulator. The temperature in the heating chamber was controlled by a potentiometer with a chromium-nickel thermocouple sensor.

The complex diffusion metallization process was carried out in the following sequence: preparation of the part for metallization and measurement of samples; packing of parts into containers and sealing of containers; loading the devices; turning it on and bringing it to operating temperature; maintaining the load at operating temperature; turning off the heating and cooling the heating chamber to 500°C; unloading the devices; air-drying the containers and opening them; cleaning the devices from mixture, cleaning and measuring parts and samples.

The surface hardness of the parts, the distribution of microhardness throughout the thickness of the coatings, structural and the wear resistance of the coatings were determined using the methodology described in [10 - 14].

The complex diffusion metallization method chosen for the restoration of worn precision parts of fuel equipment and pumps allows not only to restore linear dimensions, but also to harden the restored surfaces. The diffusion saturation method with a contact gas phase method in closed containers allows the use of saturation mixtures of any composition in various combinations of saturation elements and activators to change the linear dimensions and the required properties of the coating. At the same time, using the assumptions about two-component saturation with chromium, titan and boron, the following parameters are taken as the main ones: saturation temperature, storage time at operating temperature.

The saturation process temperature was varied from 900 °C to 1150 °C, lasting between 2-6 hours, because at this holding time and appropriate

temperature, sufficient linear dimensional increase is achieved for the restoration of the parts.

A number of preliminary experiments were carried out to justify the composition of the powder mixture and determine the possibility of using certain components in it. Based on the analysis of scientific works and the results of preliminary experiments, the following composition of the powder mixture was selected for the restoration of precision parts by diffusion borochromization, in wt. %: boron carbide - 30, chromium - 45, borax - 4, zinc - 4, activator - 3, aluminum oxide - the rest. The selection of this composition was previously studied by experiments.

The basis of laser heating of a material is the process of absorption of light flux and its transmission by alloyed steel. After heating of the material, its melting and evaporation occur. Simultaneously with these stages, diffusion and chemical processes, as well as phase changes, occur.

The amount of energy absorbed depends on the thermophysical and optical properties of the material and decreases with increasing wavelength of the radiation. Most of the laser radiation, 70 - 95%, is reflected by metals. The reflectivity of the material reaches maximum values for polished surfaces. Polished aluminum and copper reflect 97% and 99% of radiation with a wavelength of 10.6 µm (CO2 laser) at room temperature, respectively [15 -18].

The intensity of the radiation and its duration determine the main methods of laser processing: heating, melting and pulse loading. Laser heating, which causes phase changes in the surface layer, requires a minimum intensity of radiation energy (103 - 104 W/cm²) and an exposure time of 10-3 - 10-2 s, while the pulse effect requires a maximum intensity of radiation energy (108 - 1010 W/cm²) and an exposure time of 10-9 - 10-6 s.

Continuous and pulsed lasers are used to process various materials (CO2, Nd:YAG lasers and various hard-body lasers). Laser processing is carried out in air, argon, nitrogen and their mixtures. Our research is also carried out in a vacuum nanodiffusion environment.

3. Discussion and Result

Surface laser processing methods allow changing the structure and properties of the surface layer of the material with a thickness of 0.05 - 5.0 mm in a wide range, but the properties and structure of the volume of the internal part of the material remain unchanged. It is widely used in the field of laser processing of important structural parts of machines and various equipment (automobile manufacturing, aircraft manufacturing, medicine, road and agricultural machinery, power tools, oil and gas industry, mining).

As observed in the table 2, smoother surface preparations such as finishing and polishing (Ra ≈ 0.004–0.25 µm) resulted in relatively lower weight losses during all stages of processing. In contrast, more aggressive treatments like rough machining and hydrosandblasting (Ra up to 16 µm) led to significantly higher weight losses. Notably, the triple-treated samples (subjected to multiple cycles of plating) maintained the lowest cumulative losses when initial Ra values were minimized.

This variation shows elevated initial weight due to sample characteristics, but confirms that proper thermal control can maintain consistency in post-coating behavior.

Table 2 presents the measured weight loss of chrome-plated samples subjected to different surface preparation techniques. These values help evaluate how the initial roughness and mechanical processing methods affect material retention during and after the diffusion chromium plating process. Each processing method—finishing, polishing, grinding, hydrosandblasting, and rough machining—was applied to the samples prior to coating, and the corresponding surface roughness values (Ra, µm) are provided in the table.

The table details weight loss at several stages: before chrome plating, after chrome plating, and after final grinding of the chrome layer. Additionally, a "triple" treatment column reflects cumulative material loss across three sequential processing cycles. The results show a clear trend—samples with smoother initial surfaces (e.g., finishing and polishing) exhibit significantly lower weight loss at all stages compared to those treated with aggressive methods like rough machining or hydrosandblasting. For example, samples finished to Ra = 0.004–0.05 µm lost only 0.0166 g after triple treatment, whereas roughly machined samples (Ra = 10–16 µm) lost 0.0552 g.

The lower table row titled "Under 8-degree Grinding" refers to a specific surface preparation condition where grinding was performed under a shallow angle of 8 degrees. This modification led to significantly higher overall weight readings (e.g., 1.5819 g before processing) but still demonstrates consistency in behavior across post-treatment phases, with losses comparable to standard grinding. This condition was included to explore the effect of angular processing on weight stability and surface retention under similar Ra conditions.

These findings confirm the importance of initial surface quality and processing parameters in minimizing material loss during complex diffusion metallization and chromium plating procedures.

The effect of the processing quality of the parts on their properties before applying the coatings was studied. Testing of samples made of different grades of steel and subjected to various heat or thermal treatments, and galvanic coatings on them showed that the difference in the chemical composition and properties of the steel does not affect the properties of the coating, which are determined by the roughness, microhardness and porosity of the surface. The roughness of the coatings is most affected by the roughness of the base metal and the thickness of the deposit.

With an increase in the thickness of the chromium layer to 0.08 mm, the roughness of the surface increases by 1.5-2 times; a further increase in thickness increases the roughness of the surface and leads to the formation of porosity (Fig. 6).

The roughness of the coatings is most affected by the roughness of the base metal and the thickness of the deposit. With an increase in the thickness of the chromium layer to 0.08 mm, the surface roughness increases by 1.5-2 times; a further increase in thickness increases the surface roughness (Ra) and leads to the formation of porosity (N) (Fig. 5). The roughness of the chromium-plated surface depends on the regimes of the chromium coating and increases with increasing current density and decreasing temperature. An increase in the initial surface roughness with a layer thickness of 0.2 mm reduces the hardness of the coating by 10% and increases the porosity several times (Fig. 6). The change in properties during steel deposition, depending on the roughness of the initial surface, has the same character.

To assess the influence of different surface preparation methods on the durability and mass stability of diffusion-coated components, a series of weight loss measurements were conducted on steel specimens subjected to chromium plating. Table 2 presents the weight loss (in grams) of chrome-plated samples after various mechanical surface treatments, both before and after diffusion metallization. The tested processing methods included finishing, polishing, grinding, hydrosandblasting, and rough machining, each associated with a specific surface roughness (Ra) range.

The surface microprofile, as a rule, repeats the original, and with an increase in the coating thickness to 0.2 mm, the height of the micro-roughness increases by about 2 times. In this case, the microhardness and porosity of the chromium coating practically do not change.

Table 2. Weight loss of chrome-plated samples depending surface processing methods.

Type of processing	Grinding, Ra, μ	Weight loss in examples, g				
		Before processing	After processing			
			Before chrome plating	After chrome plating	Chromed samples after grinding	triple
Finishing	0,004-0,05	0,0843	0,0321	0,0872	0,0203	0,0166
Polishing	0,20-0,25	0,1014	0,0343	0,1055	0,0321	0,0308
Grinding	0,4-0,5	0,1318	0,0405	0,0224	0,0470	0,0341
Hydrosandblasting	2,5-3,2	0,2456	0,0517	0,2483	0,0520	0,0495
Rough machining	10-16	0,3018	0,0554	0,02660	0,0594	0,0552
Under 80-degree						
Grinding	0,4-0,5	1,5819	0,1435	1,543	0,1365	0,1342
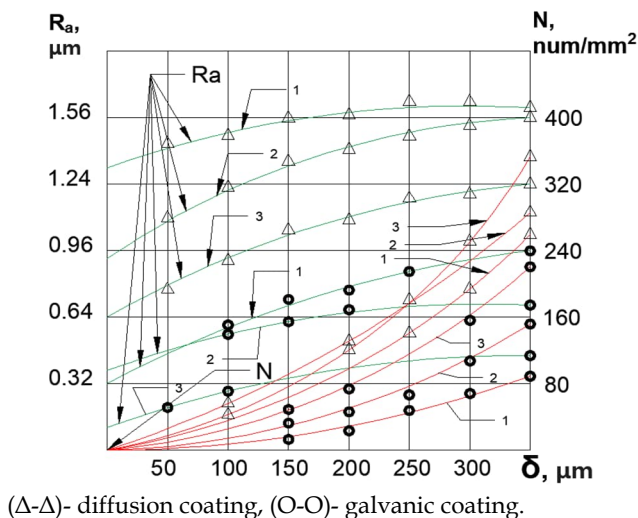
(Δ-Δ)- diffusion coating, (O-O)- galvanic coating.

1 - ХВГ, 2 - ШХ15, 3 – Р18

Figure 5. Effect of chrome layer thickness δ and surface roughness of parts before chrome plating on chrome surface roughness.

Roughening the surface of the sample metal reduces the quality of the coating and its adhesion to the base metal. Consequently, less roughness of the surfaces before coating increases the performance characteristics of the parts and reduces the total time for machining, despite the appliying of an additional operation.

Figure 5 shows how the initial surface roughness of parts and the thickness of the chromium layer (δ, in micrometers) affect the final surface roughness (Ra, in micrometers) and porosity (N, in number of pores per mm²) of the coated surface. Two different coating methods were used: laser diffusion coating (shown with triangle markers) and galvanic coating (shown with circle markers). The figure compares results for three types of steel: ХВГ (AISI L2), ШХ15 (AISI 52100), and Р18 (AISI M2), marked as 1, 2, and 3 respectively.

The vertical axis on the left represents Ra (surface roughness), while the vertical axis on the right shows N (porosity). The horizontal axis represents the thickness of the chrome coating in micrometers. Green curves and triangle markers correspond to the laser diffusion coating results for surface roughness. Red curves and circular markers correspond to the galvanic coating results for porosity.

As the thickness of the chrome layer increases, both the roughness and the porosity also increase. However, the degree of increase depends on the type of steel and the coating method. Laser diffusion coatings generally result in lower surface roughness and porosity
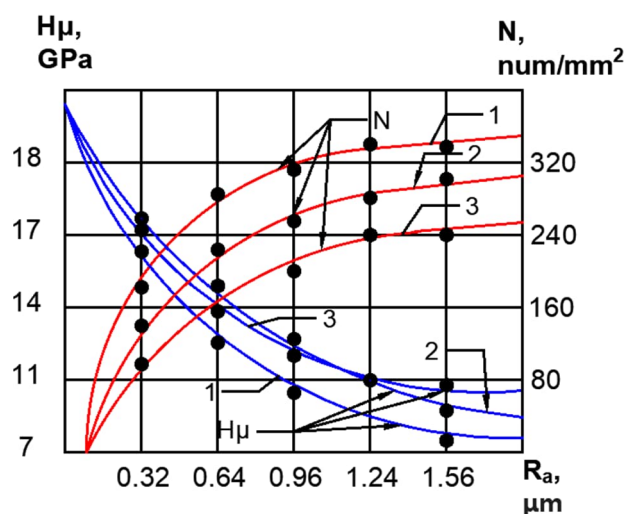
compared to galvanic coatings. Among the three steels, P18 shows the lowest porosity values overall, while ХВГ tends to have higher roughness values.

This figure highlights the importance of selecting the appropriate coating method and controlling the initial surface roughness in order to produce high-quality, wear-resistant surfaces for precision parts.

Figure 6 presents the relationship between the initial surface roughness Ra in micrometers of steel samples and two resulting properties of the diffusion chromized coatings: microhardness Hμ in gigapascals and porosity N in number of pores per square millimeter. The horizontal axis shows surface roughness Ra ranging from approximately 0.32 to 1.56 micrometers. The left vertical axis displays microhardness Hμ from 7 to 18 gigapascals, and the right vertical axis shows porosity N from 80 to 320 pores per square millimeter.

The chart includes results for three different steels: ХВГ marked as 1 which corresponds to AISI L2, ШХ15 marked as 2 which corresponds to AISI 52100, and P18 marked as 3 which corresponds to AISI M2.

Two sets of curves are shown. Blue curves represent microhardness values Hμ, and red curves represent porosity values N. Black circular points indicate the measured experimental data.

From the data, it can be observed that microhardness starts high, around 17.5 to 18 gigapascals when Ra is low at around 0.32 micrometers, and it steadily decreases to about 11 to 9 gigapascals as Ra increases to 1.56 micrometers. This indicates that smoother initial surfaces lead to higher coating hardness. For example, P18 maintains a microhardness above 11 gigapascals even at higher Ra values, showing better stability compared to ХВГ or ШХ15.

On the other hand, porosity values start lower, around 80 pores per square millimeter at Ra equals 0.32 micrometers, and increase significantly as Ra grows. At Ra equals 1.56 micrometers, porosity reaches as high as 340 pores per square millimeter, especially for ХВГ. This shows that rougher initial surfaces result in more porous coatings, which can reduce performance and durability.

In summary, Figure 6 shows that decreasing the surface roughness before diffusion chromization improves coating quality by increasing hardness and reducing porosity. Among the tested steels, P18 offers the most favorable performance, retaining higher hardness and lower porosity even as roughness increases.

1 - ХВГ, 2 - ШХ15, 3 – P18

Figure 6. Effect of surface roughness on microhardness Hμ and porosity N after diffusion chromization in coatings.

4. Conclusion

Prior to laser vacuum diffusion metallization, mechanical surface preparation is essential to ensure effective coating adhesion and uniform treatment.

The application of special pastes containing chromium, titanium, and boron components is a necessary step to facilitate successful diffusion during the metallization process.

Surface roughness was measured before and after metallization, and it was found that the thickness of the diffusion layer significantly influences the resulting surface texture.

The relationship between initial roughness and coating

quality was confirmed by studying microhardness and porosity, both of which are strongly affected by surface conditions before processing.

Overall, the findings confirm that applying diffusion-active pastes followed by laser-assisted vacuum metallization is an effective method for improving the surface hardness, microstructure, and functional durability of worn or new precision components.

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