

Every year, the world economy suffers enormous losses due to wear and corrosion of machine parts and equipment. With targeted preventive protection against wear and tear, these losses can be avoided. Along with the coating of new parts, this includes the restoration of worn parts. An effective method is the surfacing of materials with high performance properties. The quality of hardened parts depends on the properties of deposited material, so hardening material or alloy is selected taking into account the working environment of the part and the coating method.

Today there are many self-fluxing surfacing powder alloys based on nickel, copper and others, obtained by different methods.

The paper discusses the process of studying the gas-flame application of powders to increase wear resistance and adhesion strength. Experimental studies have been carried out to determine the optimal composition of the CrB<sub>2</sub> master alloy introduced into the composition of the GP-Ir40 surfacing alloy. It has been found that to obtain the hardness of the deposited metal in the range of 450–600 HV, it is necessary to introduce CrB<sub>2</sub> into the coating composition, within 10 % of the total mass. Thus, the strength of the alloy is increased by more than 54.41 HV. Tests for corrosion resistance in aggressive environments of hydrogen sulfide H<sub>2</sub>S, sulfuric acid H<sub>2</sub>SO<sub>4</sub> were carried out. The wear resistance of ground pumps was evaluated, and the service life of wear-resistant ground pump parts made of the IChH28N2 alloy was determined.

The new developed self-fluxing surfacing powder material based on iron with a hardening additive will be used to restore machine and equipment parts operating under conditions of abrasive wear, corrosion and elevated temperatures or corrosive environments

**Keywords:** powders, flame, plasma coatings, adhesion, strength, wear resistance, plasmatron, corrosion

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# DEVELOPMENT OF A TECHNOLOGY OF GAS-FLAME APPLICATION OF POWDERS TO INCREASE WEAR RESISTANCE AND ADHESION STRENGTH

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## 1. Introduction

The losses to the global economy due to wear and tear and corrosion amount to approximately \$80 billion annually, although with targeted preventive wear protection, these losses can be avoided. This includes, along with the coating of new parts, the restoration of worn-out parts of the structure and their return to economic circulation.

Currently, various technological methods are widely used to ensure the specified parameters of the surface layer of parts, taking into account the specified conditions of their operation: workloads, heating temperature, environment, duration of physical and chemical exposure.

Strengthening by surface deformation, which ensures the formation of structures with increased content of defects in the surface layer, is widely used to increase the fatigue resistance of both parts without stress concentrators and parts with stress concentrators operating at moderate heating temperatures (up to return temperatures).

Chemical-thermal and thermal surfaces – hardening processing methods (surface hardening, carburizing, nitrid-

ing, aluminizing, boriding, etc.) can dramatically change the physicochemical state of the surface layer of parts and provide the required performance properties (wear resistance, fatigue resistance, heat resistance, etc.).

The use of these methods is not only effective, but in some cases the only possible way to ensure a given resource and reliability of parts.

Welding, laser processing, ion alloying, etc. have also received practical application, some of these technological processes simultaneously increase fatigue resistance, corrosion resistance and other performance properties of the surface layer of the part.

An effective method of surface hardening of machine parts is powder spraying (surfacing) of materials with high performance properties. This method is cost-effective, since surfacing is applied only to the surfaces operating under conditions of intense wear and, as a rule, the weight of deposited material is a small fraction of the weight of the part. The durability of hardened parts is determined by the properties of deposited material; therefore, the applied material or alloy is selected taking

into account the operating conditions of the part and the applied deposition method.

As a result of through corrosion damage, the number of failures of electric submersible units (ESU) and tubing units has significantly increased, which reduces the operating time of downhole equipment, which very often does not exceed 100 days. A big problem is the low operational reliability of tubing – approximately 30 % of failures due to local corrosion of the inner surface of the pipes and leakage of threaded connections. Failures in the form of corrosive damage to the power cable and corrosive wear of fasteners are also observed (up to 50 % of cases of so-called “ESU flights” are caused by corrosive wear of studs) [1, 2]. Therefore, studies that are devoted to the gas-flame application of powders on wear resistance and adhesive strength are of scientific significance.

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## 2. Literature review and problem statement

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There are many self-fluxing surfacing powder alloys based on nickel, copper, obtained by different methods, which occupy a leading place among the materials industrially produced by various world companies such as NACA, JNCO, Battelle, Cabot, BBC, Vienna, KRUPP, etc. Alloys with a given hardness from 35 to 55 HRC such as PSR-2, PSR-3, PSR-4, etc. [3] have been developed. On this example, the standard of the enterprise of wear-resistant powder GP-Ir40, the method of applying gas-powder surfacing, was developed. The priority of the tasks is the development of a method for applying the wear-resistant powder GP-Ir40 by plasma surfacing. All these alloys are developed on the basis of cobalt, nickel and copper with various carbide-forming additives that provide the required physical and mechanical properties of the deposited (applied) coating [4]. The developed wear-resistant powder GP-Ir40 was strengthened with the addition of CrB<sub>2</sub>, which gave an advantage in the strength of the alloy. Various alloying elements are introduced into the initial composition of powder surfacing alloys to give the alloy certain physical, chemical, mechanical and self-fluxing properties. Such alloys are widely used in the practice of restoring and strengthening machine parts and mechanisms using thermal deposition technologies. According to the authors' description, this powder system is designed for gas-powder surfacing of the coating. [5]. In turn, we studied the possibility of strengthening an alloy of a similar system by adding chromium boride, and then using plasma surfacing for coating.

Strengthening and corrosion protection of parts of equipment for the oil and gas industry, at present, is one of the most important problems of these industries, the successful solution of which will dramatically reduce the consumption of ferrous metals, improve the quality and durability of machines and mechanisms, labor productivity, save material, energy and labor resources. The author considers the process of ion-plasma deposition of TiN-based coatings, by the method of condensation with ion bombardment, to strengthen the parts of the cutting tool. This method of increasing wear resistance is possible only if a strictly optimized technological process is followed. It is advisable to use such hardening technologies, where there is no thermal effect on the base of the material, and the coating process itself is implemented on complex and expensive equipment [6].

In this regard, it is relevant to strengthen and restore worn parts of equipment giving them properties that are

significantly superior to those of untreated parts, primarily the ability to resist corrosion and physical and chemical wear [7]. The author cites the results of a study where coating at a certain angle also affects quality [8]. In the literature, the schemes of design solutions of the main components of detonation installations and methods of quality control of coatings are given [9]. All this allows us to assert that it is expedient to conduct a study devoted to the process of gas-flame application of powders to increase wear resistance and adhesion strength. The main analyses of the coating properties and test methods were carried out following the example of the studies of these works.

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## 3. The aim and objectives of the study

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The aim of the study is to develop a technology for producing a new alloy, based on the previously developed self-fluxing surfacing powder alloy GP-Ir40, with the introduction of chromium boride hardening additive into its composition.

To achieve this aim, the following objectives are accomplished:

- to conduct studies of the processes of gas-flame spraying of machine parts;
- to conduct research of the deposited layer to increase corrosion resistance and adhesion strength;
- to study the wear resistance of ground pump parts.

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## 4. Materials and methods of research

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Fe, Ni, Cr, Si, Cu, B, C powders and CrB<sub>2</sub> hardening addition alloy were used as initial reagents for creating a self-fluxing surfacing powder. To develop the technology for producing a new alloy with CrB<sub>2</sub> master alloy, a self-fluxing surfacing powder alloy GP-Ir40 with a 50–160 μm fraction was used, which has the following chemical composition: Fe=38 %; C=15.1 %; Si=3.0 %; B=2.9 %; Ni=33 %.

Copper was introduced to increase the fluidity of the melt, as well as to increase the corrosion resistance of the alloy. Vanadium was introduced to increase the cold resistance of the alloy, forming hardening phases with carbon, vanadium increases the wear resistance of the alloy. An increase in carbon content is necessary for the formation of carbides, which, precipitating from the liquid solution during gas-powder surfacing, become crystallization centers and contribute to structure refinement, which, in turn, increases the strength of the alloy.

The composite material was developed by a mechanochemical method using an attritor [10, 11], the resulting powder was granulated on a planetary granulator to create a powder of the required grain size. The structure of the surfacing alloy, its physical, mechanical and operational properties were determined by standard methods. In particular, the structural analysis of the surface layers of the iron-based surfacing alloy was carried out using metallographic analysis on a metallographic workstation based on the Leica DM IRM “Wetzlar” inverted microscope (Germany), as well as scanning and transmission electron microscopy on the JEOL JXA-8230 microprobe analyzer (Japan). To determine the phase composition of the samples, the method of X-ray diffraction analysis on the D8 ADVANCE diffractometer “Bruker Elemental GmbH” (Germany) was used. The mi-

crohardness was measured on a PMT-3 microhardness tester in accordance with GOST 9450-76 by the static indentation method. The study of the adhesion strength of the surfacing layer was carried out on a TsDM10/91 tensile testing machine. The hardness test of the deposited layer was carried out on a TP-7R-1 device for measuring the hardness of materials and alloys by the Vickers method. The technological properties of the obtained granular powder mixture were examined using gas-flame surfacing on various steel samples.

To determine the phase composition of the new surfacing alloy, a D8 Advance (BRUKER) diffractometer was used. Microanalysis of the thin section was carried out on a Neophot-2 metallographic microscope at  $\times 200$ , 500, and 1000 magnifications [12–14].

To develop the technology for producing a new alloy with CrB<sub>2</sub> master alloy, a self-fluxing surfacing powder alloy GP-Ir40 with a 50–160  $\mu\text{m}$  fraction was used, which has the following chemical composition: Fe=38 %; Cr=15.0 %; Si=3.1 %; B=2.9 %; Ni=33 %; Cu=4 %; V=4.0 %.

CrB<sub>2</sub> ligature of the following chemical composition: Ti=0.08 %; Fe=0.47 %; Ni=0.52 %; B=15 %; Cr=83.43 % was used as a hardening additive. The CrB<sub>2</sub> ligature was ground for 5 minutes in a laboratory planetary mill in an alcohol environment using grinding bodies (5–8 mm bearing balls with a 1:3 powder mixture-balls weight ratio). After grinding, the average particle size of CrB<sub>2</sub> was 10–30  $\mu\text{m}$ .

For the experiment, 2 types of charge were prepared.

The first variant of the charge is the new surfacing alloy GP-Ir40, and the second variant is GP-Ir40 with the CrB<sub>2</sub> hardening additive. The charge is a mechanical mixture of the components of the initial state of the new GP-Ir40 alloy and the CrB<sub>2</sub> hardening additive, which is mechanically alloyed in an attritor. The mechanochemical activation of the charge was carried out in the attritor. Prior to the mechanochemical activation in the attritor, 1 % zinc stearate was added to the charge to prevent the charge material from sticking to the balls and to the inner surface of the drum. The charge was processed in the attritor under the following conditions:

- stirrer speed – 340 rpm;
- ball diameter – 5 mm;
- charge-balls weight ratio – 1/18;
- processing time – 2 h.

Mechanical alloying produced composite powder materials with a particle size of 10–20  $\mu\text{m}$  [15–18]. To obtain a conglomerated powder surfacing material, the initial powder material obtained in the attritor was mixed with an organic binder of 2–3 % alcohol solution of FL-98 phenolic varnish, followed by sintering in a LH15/12 chamber furnace at a temperature of 700 °C.

After sintering, the conglomerated material was crushed and sieved through a set of sieves to sort out 50–160  $\mu\text{m}$  fractions. The testing of experimental compositions of boride-strengthened powders for gas-powder surfacing was prepared in accordance with GOST 21448-75 “Surfacing alloy powders”.

Surfacing was carried out with a propane-oxygen torch with a tip # 5, manufactured according to TU 200 Kaz. SSR 210-84, under the patent # 1276 RK. Compressed gases were used in surfacing: oxygen under GOST 5583-78 and propane under GOST 20448-2018. The standard sample was made of 45 steel under GOST 1050-88, dimensions 30×45×11 mm. Gas-powder surfacing was carried out by applying a 1.21.5 mm thick surfacing layer under the following conditions:

- oxygen pressure at the torch inlet – 0.9 MPa;
- propane pressure at the torch inlet – 0.12 MPa;
- oxygen consumption – 750 l/h;
- propane consumption – 700 l/h;
- new surfacing alloy consumption – 50 g/min;
- surfacing layer thickness – 2–3 mm.

The surface of the surfacing layer was finished with a green silicon carbide abrasive tool. The coating does not have pores and slag inclusions.

During laboratory tests, the following equipment was used: P3177 pistol for flame spraying of protective coatings, DB 2432 hydraulic press, KSO-130-I-FV-M abrasive-jet chamber, a vernier caliper in accordance with GOST 166-89. The main tool for spraying and surfacing of powder materials, the plasma method was also used.

The most high-performance gas-flame method is plasma, based on the creation of an electric arc in which gas (air, argon and others) is heated.

In our studies, from gas-flame surfacing methods (spraying) of wear-resistant powders, plasma is more cost-effective, which has found very wide application in the industry (cutting of steels, destruction of various materials, gas-plasma surfacing).

The plasma torch for spraying is designed for plasma spraying of metal and ceramic powder materials on metal and non-metal surfaces.

A direct current source with an open-circuit voltage of at least 300 V and an installed power of at least 80 kW is used as a power source for the plasmatron.

Table 1 shows the technical characteristics of the plasmatron.

Table 1

Technical characteristics of the plasmatron

Parameter	Norm
Working current, A	70÷250
Working voltage at the plasma torch (when operating in air), V	180÷270
Plasmatron power, kW, no more	70
Operating mode, PV, %	100
Water consumption for plasmatron cooling (at a plasmatron inlet pressure of 490.3 kPa), g/s, not less	270
Productivity for sprayed material, kg/h, no more:	
For aluminum oxide (Al <sub>2</sub> O <sub>3</sub> );	10
For metal powders	30
Coefficient of powder material use when spraying on a steel sample of the “Sheet” type with the size of 300×300×3 mm, not less	0.7
Plasmatron weight without spare parts and communications, kg	3

Fig. 1 shows a stand for plasma spraying of metal powders, made on the basis of a lathe with a movable carriage, on which a plasmatron is installed. The sprayed part is fixed in the chuck of the machine and the tailstock.

Fig. 2 shows the parts obtained during processing on the plasmatron.

To provide plasma surfacing of the resulting composition with an air-plasma torch:

- open circuit voltage – 320 V $\pm$ 5 %;
- operating current regulation limits – from 200 to 500 A;
- working voltage on the arc – 270 V;
- plasma-forming gas – air;



- rectifier cooling – forced air;
- plasmatron cooling – water;
- water consumption – 6 l/min;
- new surfacing alloy consumption – 120 g/min;
- surfacing layer thickness – 1–3 mm.
- nozzle to part distance – 15–17 cm.

Tables 2, 3 show the modes of spraying of metal and ceramic materials.

Now almost all metal powders are sprayed at a plasma gas flow rate of 3 g/s.

Basically, ceramics are sprayed at a plasma gas flow rate of 1.5 g/s.

When working in air, a cathode with a hafnium or zirconium working insert is used; when working on nitrogen, argon, hydrogen, helium – with a tungsten insert.

Taking into account the environmental, technological and economic requirements, this research direction, in particular, modern methods of applying coatings, methods of their testing are subject to standardization and certification of these processes. The need for standardization of welding (coating) procedures has arisen in connection with the introduction of international and European standards for quality management systems, in which welding is considered a special process, “in which confirmation of conformity of the final product is difficult” (ISO 9000:2000).



Fig. 1. Experimental stand for surfacing metal powders: 1 – lathe; 2 – movable machine carriage; 3 – three-jaw chuck; 4 – tailstock; 5 – machining part; 6 – plasmatron; 7 – control levers



Fig. 2. Obtained parts during processing on the plasmatron: a – on a cylindrical surface; b – on a flat surface

Table 2

Modes of spraying of metallic materials

Gas plasma consumption, g/s	Mass average temperature of plasma, deg. K	Mass average velocity of the plasma jet, m/s	Sound speed at plasma temperature, m/s
1.5	6,750	1,490	1,840
2	6,500	1,919	1,740
2.5	6,300	2,207	1,690
3	6,000	2,415	1,608

Table 3

Modes of spraying ceramic materials

Gas plasma consumption, g/s	Mass average temperature of plasma, deg. K	Mass average velocity of the plasma jet, m/s	Sound speed at plasma temperature, m/s
1	7,000	708	1,914
1.5	6,750	970	1,840
2	6,500	1,225	1,740

In the requirements of ISO 9001:2008, it is written that: “The organization must confirm all production and service processes, the results of which cannot be verified by means of consistent monitoring or measurement, so that their deficiencies become apparent only after the start of use of the product or after the provision of the service”.

Detailed requirements for the quality of welding (coating) are defined by the ISO 3834 standards for quality assurance in welding production.

So, to identify the qualitative and quantitative indicators of the GP-Ir40 powder alloy, corrosion resistance and adhesion tests of the alloy were carried out.

The GP-Ir40 powder alloy has the following chemical elements in the appropriate percentage: Fe=38 %; Cr=15.0 %; Si=3.1 %; B=2.9 %; Ni=33 %; Cu=4 %; V=4.0 %.

To determine the properties of the GP-Ir40 powder alloy, the following tests were carried out on standard samples in accordance with GOST 1050-80 (grade ST 3).

Corrosion resistance test. During the tests, a 30 % H<sub>2</sub>SO<sub>4</sub> solution was chosen as an aggressive medium. The density of the solution at a temperature of 200 °C was ρ=1.83 g/cm<sup>3</sup>. Samples # 1, 2.

Dimensions:

- sample # 1, sample # 2;
- length  $H=48$  mm,  $H=46$  mm;
- width  $W=33$  mm,  $W=32$  mm;
- height  $B=9$  mm,  $B=10$  mm;
- area  $S=4812$  mm<sup>2</sup>,  $S=4,504$  mm<sup>2</sup>;
- mass  $m^1=109.73$  g,  $m^2=103.077$  g.

Test to determine the effect of coating thickness on the outer cylindrical surfaces on the adhesion of the coating to the substrate. The following equipment was used during the tests: P3177 gun for gas-flame spraying of protective coatings, DB 2432 hydraulic press, KSO-130-I-FV-M abrasive blasting chamber, caliper according to GOST 166-89.

Test to determine the effect of spraying distance on the adhesion of the coating to the substrate. The following equipment was used during the tests: P3177 gun for gas-flame spraying of protective coatings, DB 2432 hydraulic press, KSO-130-I-FV-M abrasive blasting chamber, caliper according to GOST 166-89. Standard samples of 45 steel according to GOST 1050-88 with dimensions of 30×45×11 mm were used for coating.

## 5. Results of research of the process of gas-flame application of powders

### 5.1. Studies of the effect of flame spraying of machine parts on qualitative and quantitative indicators

Fig. 3 shows micrographs of the obtained surfacing powder. From the obtained micrographs, it can be concluded that

the particle size of the powder is 50–160 μm, and the shape of the particles is spherical or oval.

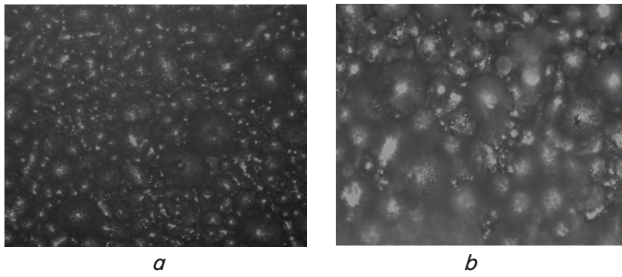


Fig. 3. Micrographs of the powder with magnification: a – ×200; b – ×500

The chemical composition (Fig. 4), the structure of powders and composite coatings were investigated using a spectrometer. The used spectrometer does not determine boron and carbon, silicon, therefore, the graph shows the initial data on their content in the alloys under consideration. The rest of the alloy elements correspond to their content in the original powder. The effect of adding CrB<sub>2</sub> on changes in the chemical composition of the GP-Ir40-based alloy is shown in Fig. 2.

According to the results of X-ray structural analysis (Fig. 5), it was found that the structure of the alloy is a composition consisting of a relatively strong and plastic iron-nickel matrix and strengthening phases in the form of carbides and borides such as FeB; Cr<sub>2</sub>B; Cr<sub>2</sub>B<sub>2</sub>; Cr<sub>3</sub>C<sub>2</sub>; Cr<sub>5</sub>B<sub>3</sub>; Cr<sub>7</sub>C<sub>3</sub>; Cr<sub>23</sub>C<sub>6</sub>; Fe<sub>3</sub>C; Cr<sub>7</sub>BC<sub>4</sub>; Fe<sub>3</sub>C, silicon nickelide Ni<sub>2</sub>Si<sub>5</sub>. The presented material is an iron-nickel low alloy with a typical two-phase structure. The 12.1 % increase in the chromium content in the two-phase Fe-Cr structure of the GP-Ir40+10 % CrB<sub>2</sub> alloy in comparison with the similar GP-Ir40 alloy structure should also be noted.

The microhardness was also measured on the Vickers scale separately for the two alloys and the diffusion zone, which shows the hardness value on the steel baseplate in the diffusion zone and on the surface of the investigated powder conglomerated alloy. The obtained microhardness values of the deposited surface in the fusion zone of the test specimen are shown in Table 4.

It should be noted that microhardness increases towards the deposited surface of the test specimen.

The distribution of coating microhardness values is uniform without obvious hardness variations. The values range within 400...500 MPa, implying the uniform distribution of borides and carbides, the homogeneity of the structure throughout the entire area of the surfacing coating (Fig. 6).

The coating microhardness was determined on thin sections of samples # 1, # 2 with a 2 mm thickness by 4–7 measurements of the diagonal of the indent.

The obtained microhardness values for the deposited surface of the sample are shown in Table 5.

Table 4

Microhardness measurement results for the test specimen

Prints	Vickers hardness, HV 98.0665 N		
	Steel baseplate	Diffusion zone	Specimen material, 90 % GP-Ir40+10 % CrB <sub>2</sub>
1	382.72	381.40	456.72
2	362.75	426.57	470.63
3	375.41	428.62	530.29
4	359.34	443.42	485.18
Average	HV=370.34	HV=420.00	HV=485.70

Table 5

Microhardness measurement results for the section of sample # 1 deposited with GP-Ir40 and GP-Ir40+10 % CrB<sub>2</sub> alloys

Prints	GP-Ir40	GP-Ir40+10 % CrB <sub>2</sub>
	Vickers hardness HV 98.0665 N	
1	482.71	563.64
2	519.13	546.15
3	487.67	542.09
4	492.71	547.96
Average	HV=495.55	HV=549.96

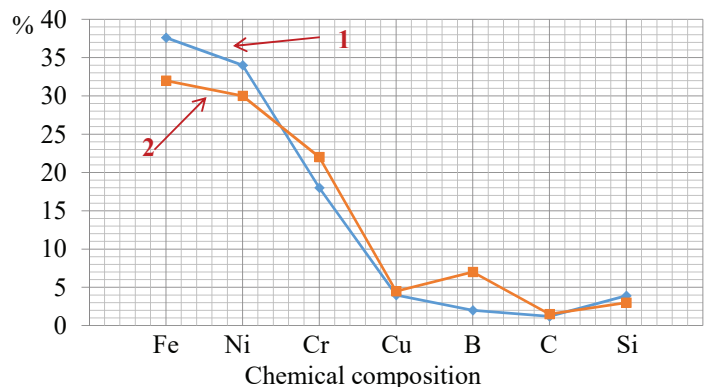


Fig. 4. Chemical composition of surfacing powder: 1 – powder alloy GP-Ir40 – 100 %; 2 – powder alloy GP-Ir40 90 % + 10 % CrB<sub>2</sub>

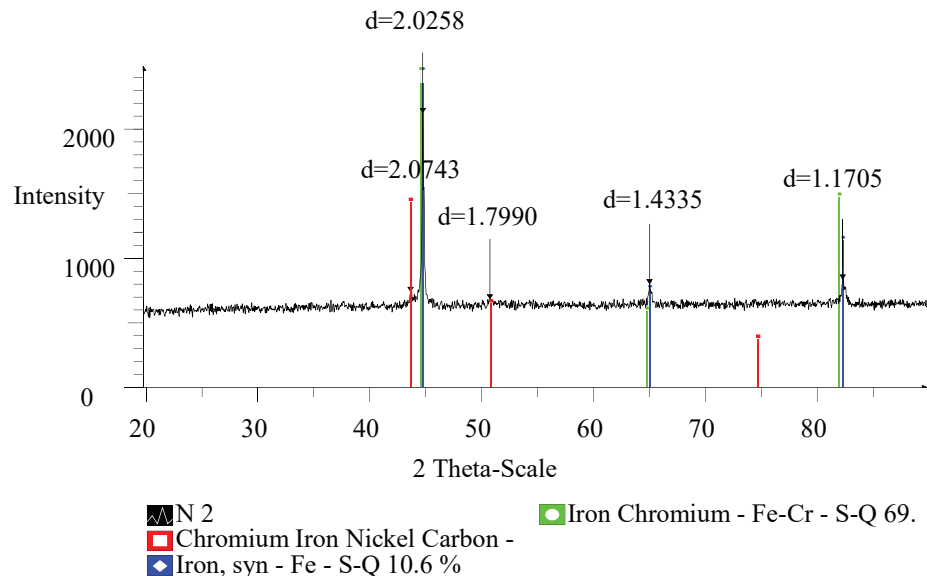


Fig. 5. Results of X-ray structural analysis of GP-Ir40+10 % CrB<sub>2</sub>



According to the microhardness measurement results, the average microhardness value of the specimen of the deposited boride-hardened alloy increased by 54.41 HV in comparison with the initial alloy obtained by surfacing with GP-Ir40 material.

The study of the fusion zone of the new boride-hardened alloy was carried out on a metallographic microscope at  $\times 200$  and  $\times 500$  magnifications. The section was prepared from a specimen deposited with a conglomerated powder alloy of the following composition: 90 % GP-Ir40 +10 % CrB<sub>2</sub>. Fig. 7 shows the boundaries of the deposited alloy diffusion zone. The formed layers of the diffuse zone are, apparently, a consequence of peritectic reactions, according to the state diagram of the Fe-Ni-Cr-B system.

Fig. 8 shows the results of wear assessment for the specimens with a deposited surface and a surface hardened to 55HRC compared to 20GL steel pads. This made it possible to assume that when parts work in friction units, one can not be afraid of a decrease in their durability as a result of wear of a part restored by GP-Ir40+10 % CrB<sub>2</sub> alloy surfacing.

Metallographic analysis was carried out for specimen # 1 deposited with GP-Ir40 alloy and for specimen # 2 deposited with GP-Ir40+10 % CrB<sub>2</sub> alloy. Microanalysis was carried out on a Neophot-32 metallographic microscope at  $\times 200$ ,  $\times 500$  magnifications.

Fig. 9 shows a homogeneous polyhedral, equiaxial block structure with a coarse-grained to fine-grained structure transition zone and localized solid copper solution particles. Along the grain boundaries, there are chains of numerous precipitates of excess phases of two types – dark and less often – light, possibly iron and chromium carbides.

Deposited layer of the part with GP-Ir40 surfacing alloy

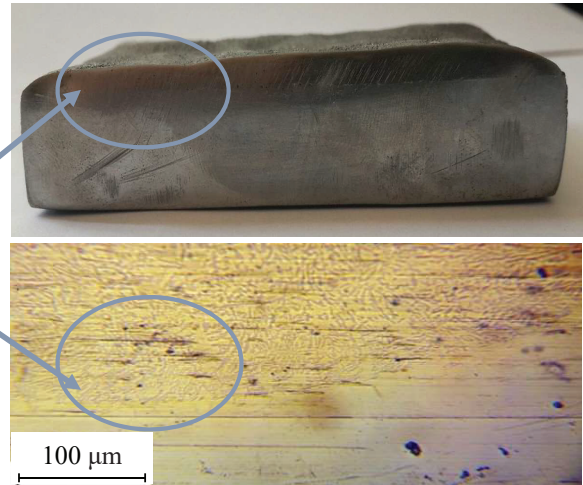


Fig. 7. Microstructure of the deposited metal (GP-Ir40+10 % CrB<sub>2</sub>) with the base metal,  $\times 500$  magnification

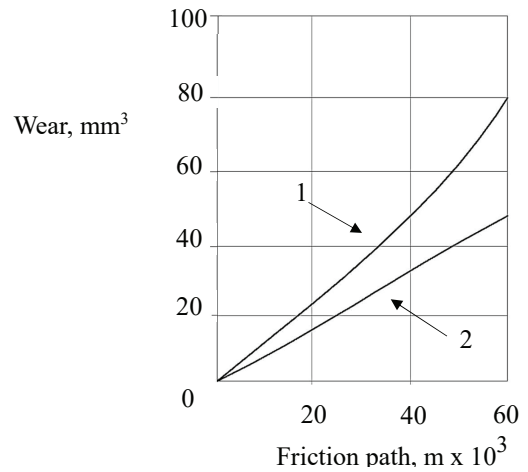
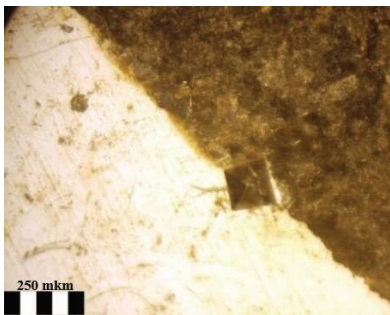


Fig. 8. Wear rate of new alloy and steel: 1 – new GP-Ir40 +10 % CrB<sub>2</sub> alloy; 2 – 45 steel, 55 HRC hardness



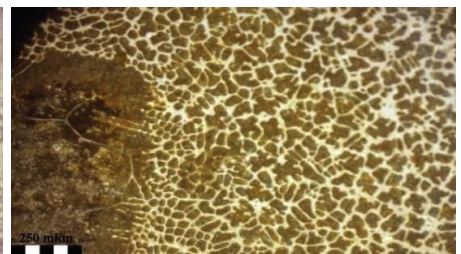
a



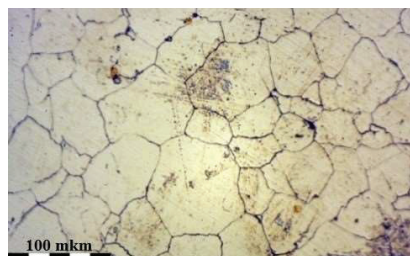
b



a



b



c



d

Fig. 6. Size of the imprint on the thin section of the sample: a – GP-Ir40; b – GP-Ir40+10 % CrB<sub>2</sub>

Fig. 9. Microstructure of the deposited layer with GP-Ir40 (a) and +10 % CrB<sub>2</sub> alloy: a –  $\times 200$  magnification GP-Ir40; b –  $\times 200$  magnification GP-Ir40+10 % CrB<sub>2</sub>; c –  $\times 500$  magnification GP-Ir40; d –  $\times 500$  magnification GP-Ir40+10 % CrB<sub>2</sub>

Fig. 7 shows coarse grains in the microstructure of the alloy, which consist of ultrafine subgrains. Polyhedral ferrite grains – a solid carbon solution in  $\alpha$ -iron and pearlite – possibly a eutectoid mixture of ferrite with iron and chromium carbide.

The phases formed mainly inside the grains and along the grain boundaries in some areas increase in size up to 1  $\mu$ m, forming a block structure. From the data obtained, it can be concluded that the obtained surfacing powder with the addition of GP-Ir40+10 % CrB<sub>2</sub> has good hardness and better properties compared to the GP-Ir40 surfacing powder.

**5. 2. Investigation of the GP-Ir40 deposited layer for corrosion resistance and adhesion**

According to the test results, the following was determined: changes in sample weight; corrosion rate; corrosion resistance (Table 6).

Summary table of test results

Sample #	Material	Corrosive medium	Sample weight, g		Weight change, g	Loss from corrosion	Corrosion resistance
			prior to the test	after the test			
1	GP-Ir40	30 % H <sub>2</sub> SO <sub>4</sub>	109.73	109.21	0.52	0.000074	score 3
2	GP-Ir40	30 % H <sub>2</sub> SO <sub>4</sub>	103.077	102.38	0.697	0.000082	score 4

Testing in corrosive media. During the tests, Moni-cor-2M measuring tools to determine the corrosion rate, corrosive media hydrogen sulfide H<sub>2</sub>S, sulfuric acid H<sub>2</sub>SO<sub>4</sub> (acidic media) were used.

1. Test results:

The following results of corrosion tests of the alloy in hydrogen sulfide environment H<sub>2</sub>S (sample # 3) were obtained (Table 7).

Table 7

Results of corrosion tests of the alloy in hydrogen sulfide H<sub>2</sub>S

Coating appearance	light gray
Coating adhesion	at least 50–80 MPa
Coating microhardness	at least 500 HV
Mass coating corrosion rate	0.089 mm/year
Depth coating corrosion index	0.101 mm/year
Index of zitting corrosion	0.014 g/m <sup>3</sup> *hour
Electrochemical corrosion potential	-0.190 V

2. The following results of corrosion tests of the alloy in sulfuric acid H<sub>2</sub>SO<sub>4</sub> (sample # 4) were obtained (Table 8).

Table 8

Results of corrosion tests of the alloy in sulfuric acid H<sub>2</sub>SO<sub>4</sub>

Coating appearance	light gray
Coating adhesion	at least 55–82 MPa
Coating microhardness	at least 500 HV
Mass coating corrosion rate	0.08 mm/year
Depth coating corrosion index	0.115 mm/year
Index of zitting corrosion	0.02 g/m <sup>3</sup> *hour
Electrochemical corrosion potential	-0.23 V

Test to determine the bond strength of the coating to the substrate.

The following test results were obtained (samples # 5, 6):

- specimen base hardness – HRC 57;
- coating microhardness – HV 1330;
- abrasive blasting,  $\mu$ m – 63;
- thread ripping, mm – 1.28;
- average pore diameter, mm – 0.1–0.15.

The following test results were obtained (samples # 7–9):

- sample hardness – HRC 42–46;
- coating microhardness – HV (1,560-1,670);
- ground surface porosity, pore/cm<sup>2</sup> – 1–3;
- adhesion of sample coatings, MPa: # 7 – 1.147; # 8 – 1.432; # 9 – 1.687.

Test to determine the effect of spraying distance on the adhesion of the coating to the substrate (Fig. 10–12).

Table 6



Fig. 10. Coated specimens prior to corrosion testing



Fig. 11. Coated specimens after corrosion testing



Fig. 12. Samples with cleaned surface from traces of corrosion

Test results (samples # 10, 11):

- specimen base hardness, HRC – 43–45;
- coating microhardness, HV – 1,640–1,680;
- ground surface porosity (average pore diameter, mm – 0.05).

Average number of pores per 1 cm<sup>2</sup> of the surface as a function of the nozzle to sample distance L (Fig. 10–12):

- 90 mm – 3–5; 80 mm – 1–3;
- adhesion of coatings (by shear method depending on L, MPa):
- 90 mm – 20.2; 80 mm – 30.99.

**5. 3. Evaluation of wear resistance of ground pump parts**

There is a huge problem of increasing the service life of working parts of centrifugal groundwater pumps for pumping liquids with solids (up to 45 % and more).



By moving the abrasive slurry during operation, pump parts are subjected to intense wear and tear by the abrasive particles moving in the flow (Fig. 13).

All parts can be divided into two groups according to the nature of wear.

The first group includes the impeller and the outlet, whose flow channels are subjected to the highest degree of wear. When pumping slurries with coarse solids, these parts are also subject to impact damage [19].

The most intensive wear occurs on the impeller blades at the inlet and outlet, the inner surfaces of the impeller discs (Fig. 13, *b*), the outlet surfaces in the area of the design cross-section, the entrance to the diffuser, as well as in the area of the outlet tongue. The suction branch pipe is subject to much less wear.

The catastrophic size of hydro-abrasive destruction of pump impellers testifies to the great destructive power of the water flow containing abrasive particles [20].

The second group includes parts that wear out as a result of the flow of fluid from the cavity with higher pressure to the cavity with lower pressure: armor discs (Fig. 14), outer wheel discs, seal parts both on the suction side and the gland seal assembly. Wear of these parts, as compared to the parts of the first group, increases when transporting hydraulic mixtures with fine solid inclusions [20, 21].

The pump casing is less affected by abrasion (Fig. 15). The peripheral walls are affected the most by abrasive particles and the side walls of the pump casing channel the least. Wear here affects the places before the pulp exit into the pipeline, where its flow develops the highest velocity. The wear is in the form of through holes. Wear of the outlet walls depends on the distribution of the flow velocity of the mixture and the concentration of solids.

The main part of the spare parts is impellers – up to 50 %, armored discs account for 25 %, branches and other parts – 25 %. The service life of the wearing parts of ICH28N2 alloy soil pumps is given in Table 9.

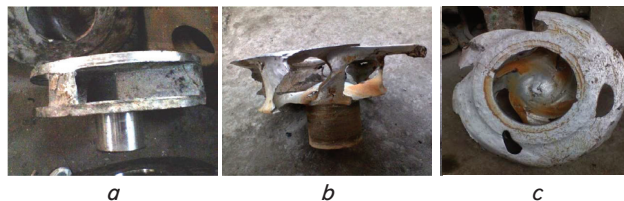


Fig. 13. Impeller of soil pump 8Gr-8: *a* – new impeller; *b* – worn impeller; *c* – worn impeller

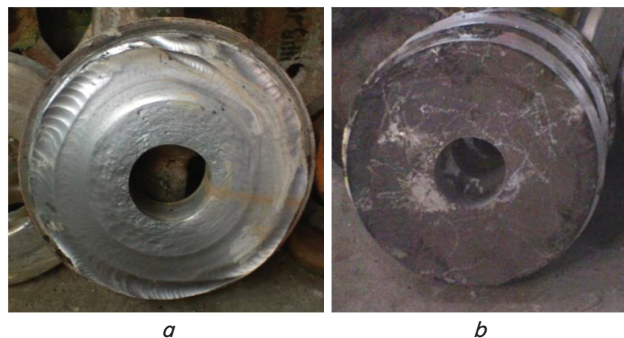


Fig. 14. Armor plate of the pump 8Gr-8Gr: *a* – after operation, *b* – new

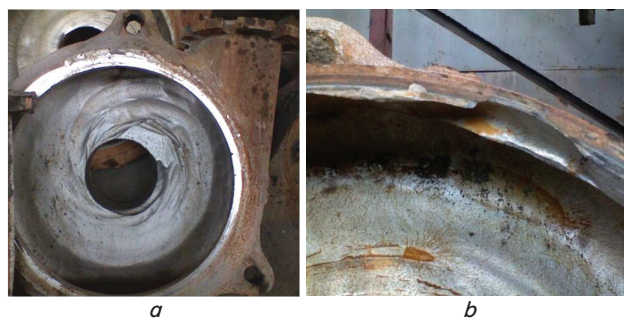


Fig. 15. Wear of the ground pump body 8Gr-8: *a* – general view; *b* –  $\times 5$  magnification

Table 9

Service life of ICH28N2 alloy ground pump parts, days

Factories	Grinding stage, product and density	Pump type	Parts			
			impeller	ullage	cover disk	antifriction bearings
Severe working conditions						
Zhezkazgan	I, up to 50 % solid	8Gr-8T	15	45	30	65–70
Zhezkazgan	II, up to 65 % solid	8Gr-8T	25	75	50	80–90
Zhezkazgan	Concentrate, up to 65 % solid	5Gr-8CC	90	90	90	120–130
Zhezkazgan	Tailings, up to 28 % solid	28Gr-8T	150	80	30–40	110–120
Leninogorsk	Tailings, up to 25 % solid	20Gr-8	80–85	55–60	55–60	220
Average working conditions						
Tekeli	I, intermediate product, 28–40 % solid	8Gr-8T	18–20	18–20	16–18	80–100
Tekeli	II, intermediate product, 20–40 % solid	8Gr-8T	80–100	80–100	65–80	80–100
Tekeli	Tailings, 10–12 % solid	12Gr-8T	50–65	55–65	25–30	165–180
Easy working conditions						
Kentau	I, 36–38 % solid	8Gr-8T	45–50	45–50	45–50	65
Kentau	II, 30–32 % solid	8Gr-8T	100–120	100–120	100–120	95
Kentau	III, 25–27 % solid	8Gr-8T	170–190	170–190	170–190	125
Kentau	Tailings	12Gr-8T	190–210	190–210	190–210	125



Pumps wear out due to the contact of solid particles moving in the liquid with the walls of the pump flow channels. In the impeller there is a separation of particles by size. Larger particles, the trajectories of which are steeper than the lines of fluid currents, do not reach the working surface of the blades at all. The blade is only flowed by the flow with small particulate matter suspended in it [22].

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## 6. Discussion of experimental results of the study of the process of gas-flame powder deposition for wear resistance and corrosion resistance

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According to the micrograph of the modified composition with the addition of the CrB<sub>2</sub> strengthening additive, it can be concluded that the powder size is 50–160 microns (Fig. 3). This is similar to the size of the most common powders used on a variety of coating equipment.

The effect of CrB<sub>2</sub> addition on the change in the chemical composition of the alloy was determined using a spectrometer. According to the results of the study, it can be found that the shares of strengthening elements of the chromium and boron alloy increased to 22 and 7%, respectively (Fig. 4).

The results of X-ray phase analysis also show that the structure of the alloy is a composition of a relatively strong and ductile iron-nickel matrix and strengthening phases in the form of carbides and borides.

When measuring the microhardness on the Vickers scale, the hardened composition of the alloy showed a strength higher by 54.41 HV (Table 5).

According to the analysis on a metallographic microscope, at  $\times 200$ ,  $\times 500$  magnifications, it can be seen that the alloy strengthened with the addition of CrB<sub>2</sub> has homogeneous structure, with coarse-grained to fine-grained structure transition. According to metallographic analysis, we can say that the resulting composition with the addition of CrB<sub>2</sub> has good hardness and better properties compared to the GP-Ir40 powder (Fig. 9).

The influence of corrosive environment on physical and chemical wear of equipment parts with wear-resistant coating. Resistance of steels against local corrosion is determined by a number of factors. Operational nature – content of aggressive gases, mineralization of aqueous phase, etc., and of metallurgical origin – chemical, structural-phase composition of alloys. And also, the presence of special alloying elements, non-metallic inclusions of special type.

The main factors that influence the chemical and structural-phase composition of the alloys, the presence of special alloying elements, non-metallic inclusions of a special type and a number of other factors are also of metallurgical origin.

Ensuring corrosion resistance and increasing service life of oil and gas production equipment is one of the most acute problems faced by pipe manufacturers. Along with protective coatings on pipes and the use of corrosion inhibitors, the production of corrosion-resistant pipes for use in certain types of environments is a topical issue [23].

Industrial and laboratory tests were carried out to obtain and confirm the provided qualitative and quantitative indicators of the powder alloy.

As a rule, the main factor influencing the corrosion resistance of pipes is considered to be the aggressiveness of

the extracted and transported medium. However, despite its obviousness, this approach seems to be very simplified. In reality, pipelines are subjected to various influences varying both in time and space. The development of local corrosion is affected not only by the aggressiveness of the transported media, but also by the flow mode of the gas-liquid mixture, the type of pipeline material used, the steel microstructure, and the mechanical and corrosion properties of the pipe material.

During the tests, a 30 % H<sub>2</sub>SO<sub>4</sub> solution was used as an aggressive medium. According to the test results, the main characteristics were determined: changes in the mass of the samples – from 0.52 to 0.697 gm and corrosion resistance from 3 to 4 points (Fig. 6).

Tests were also carried out in aggressive environments of hydrogen sulfide H<sub>2</sub>S, sulfuric acid H<sub>2</sub>SO<sub>4</sub>. The results of these tests showed that the coating characteristics such as adhesion, microhardness, mass and depth corrosion index meet the high requirements of modern mechanical engineering.

Mechanical tests of the applied coating were carried out to determine the adhesion strength of the coating to the base, to determine the effect of the coating thickness on the adhesion, and to determine the effect of the nozzle to sample distance on the adhesion and the number of pores on the coating. Thus, it is determined that the thickness of the coating and a smaller distance increase the adhesion of the coating and reduce the number of pores by almost half.

The new developed iron-based self-fluxing powder surfacing material will be used for the restoration of machine parts and equipment working under the influence of physical and chemical wear, corrosion, in aggressive environments, at elevated temperatures.

A characteristic feature of many oil and gas fields in the late stage of development is the high water cut of the product. Corrosion of the internal surface of pipelines (ulcerous, grooved, bacterial), which has a local nature, is the main cause of failure of field pipelines [24, 25].

The wear resistance of ground pumps has been evaluated. The wear resistance of ground pump parts is substantiated and their further restoration by the gas-plasma method is carried out. The service life of IChH28N2 alloy ground pump parts is calculated.

The priority of tasks for subsequent studies is to perform similar test work on full-scale ground pump parts. To conduct research on full-scale parts, first of all, it was necessary to determine the methodology for performing the work, as well as to perform research on standard samples.

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## 7. Conclusions

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1. A test procedure for gas-flame surfacing of machine parts on an experimental stand for gas-flame surfacing of standard samples has been developed. The technological process of gas-flame supersonic spraying of coatings made of metal powders and powder alloys on equipment parts to improve or restore their performance, as well as to give the sprayed surface corrosion-wear-resistant and adhesion-proof protective properties is proposed. The optimum composition of CrB<sub>2</sub> ligature to be introduced into the composition of a new cladding alloy GP-Ir40 has been

determined. It was found that to obtain a 450–600 HV hardness of the clad metal, it is necessary to introduce 10 % of the total mass of the coating into the composition, %. According to X-ray diffraction analysis, it was found that the composite cladding alloy GP-Ir40 with 10 % chromium-boron introduced after mechanical alloying and melting, the composition looks like iron-nickel matrix with evenly distributed borides and carbides of iron, chromium, nickel, which is confirmed by the increase in the microhardness of the clad metal from 495.55 to 549.96 HV units.

2. On the basis of self-fluxing alloy GP-Ir40 with chromium boride  $\text{CrB}_2$  hardening additives, it is possible to create coatings with high hardness by adding chromium borides to the alloy before gas-powder surfacing, which provides maximum wear resistance of the coating, characterized by a uniform distribution of hardening crystals over the entire cross-section, which is achieved by melting the coating layer at a temperature of 1000–1100 °C. The new nanostructured corrosion protection coating is corrosion resistant to hydrogen sulfide ( $\text{H}_2\text{S}$ ), sulfuric acids ( $\text{H}_2\text{SO}_4$ ) (acidic media) and on the scale of corrosion resistance of metals is 3 points “Very resistant”, and its level is not less than level V NACE MR 0175 ISO 15156.

The nanostructured nanocorrosion protective coating is comparable to stainless steel with a 12Cr18N9T-type sublayer and has:

- specimen base hardness – HRC 57;
- coating microhardness – HV 1,330;
- abrasive blasting – 0.45;
- average pore diameter, mm – 0.1–0.15;
- pores, pores/cm<sup>2</sup> – 1–3;
- adhesion of sample coating, MPa: # 7 – 1.147; # 8 – 1.432; # 9 – 1.687.

3. The study of the wear resistance of ground pump parts allows expanding the work on the use of the gas-plasma method of spraying (surfacing) them, thereby obtaining the operational life of the work. At the moment, the risk groups of wear of ground pump parts have been studied, the service life of wear-resistant ground pump parts made of the IChH28N2 alloy has been determined at factories in Kazakhstan such as Zhezkazgan, Tekeli and Kentau. Priority directions in the restoration of the most frequently worn ground pump parts have been identified, which poses the task of further research work on the application of coatings on full-scale ground pump parts. In the course of the study, the wear resistance was evaluated and the service life of ground pump parts per day was determined.

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