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APPLICATION OF POWDER MATERIALS AND FUNCTIONAL COATINGS

Using Metal-Sprayed Coatings to Protect Submersible Electric Pump Motors from the Impact of Complicating Factors in Oil Wells

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Abstract—This paper presents an overview of the results of the application of metal-sprayed coatings to protect the outer surface of electric submersible pumps (ESP) from the effects of complicating factors in oil wells. The metal-sprayed coating is applied using hot spraying, and the choice of the method is based on the chemical composition, the materials that are used, and the properties of the finished coating. The most common coatings on the Russian market include monel and austenitic stainless-steel alloys applied by arc metallization or high velocity spraying. Traditional coatings obtained by thermal spraying are characterized by an insufficiently high level of physical, mechanical, and chemical properties. Studies of the abnormal cases of submersible electric motors (SEMs) have shown that the most significant disadvantages of the applied coatings include insufficient resistance to mechanical shock, as well as abrasive wear; higher electrochemical potential in relation to the base metal; violations of the application technology; and significant coating porosity. One of the main reasons for the observed disadvantages is a limited number of traditionally used methods and materials. To solve the problem of using protective SEM coatings and significantly increase their properties, service life, and economic efficiency, it is necessary to use modern scientific achievements in the development of coatings to protect metal surfaces from wear and corrosion, namely, to expand the number of coating methods and materials, work out a methodology for assessing the quality of coatings, and develop a methodology for assessing the economic efficiency of protective coatings. Solving these problems will allow us to make a reasonable technical and economic choice of a specific SEM coating for specific operating conditions.

Keywords: metal-sprayed coating, thermal spraying, submersible motors, corrosion, wear, mechanism

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INTRODUCTION

The development of the oil industry includes several stages reflecting both the scale of oil and gas consumption and the degree of complexity of their production. The current state of the oil industry in the Russian Federation is characterized by complicated conditions of field development, which is caused by low production rates due to high oil viscosity and high aggressiveness and water rate. Almost the entire well stock is operated in a mechanized way, mainly using electric submersible pumps (ESPs) [1]. A multisection ESP is driven by a submersible electric motor (SEM) and delivers oily liquid (fluid) from the well to the tubing [1].

The following is an overview of protection of submersible pumping equipment from complicating factors that contribute to a decrease in service life and premature failure. The use of metal-sprayed coatings (MSCs) due to the high physical, mechanical, and chemical properties is the most effective method of protection. Nevertheless, there have been repeated cases of loss of life associated with MSC destruction [2, 9]. According to studies, the main reasons for the destruction of the SEM coating include mechanical damage, low barrier properties, abrasive wear, and noncompliance with the application technology. When choosing one or another type of coating, it is necessary to pay special attention to the ability of the coating to resist the specified destruction mechanisms, for which it is necessary, first and foremost, to develop control methods that simulate the destructive effect.

OPERATING CONDITIONS AND COMPLICATING FACTORS

Clogging with mechanical impurities and salt deposition prevail among the main factors leading to ESP failure [2]. The statistics of the reasons for ESP failures shows that, for high-rate wells, a high content of mechanical impurities is one of the main mining problems [3]. Their presence represents a significant problem for expensive equipment with abrasive wear and the jamming and clogging of working bodies with solid particles.

The influence of salt deposits is considered in [4]. Salt deposition, as a rule, occurs due to the oversaturation of water with sparingly soluble salts with changes in temperature, pressure, pH, or during gas emission. The greatest effect of salts is observed on the ESP impellers, on the surface of which, when heated during operation, salt deposits and scale are formed, which, as they increase, reduce the bore diameters.

The possibility of precipitation of asphaltene deposits depends on the oil chemical composition, temperature, water cut, intensity of gas release, and bottomhole pressure. The fallout of asphaltene deposits significantly reduces the flow area of the tubing until production stops, which is caused by the formation of deposits in the bottomhole formation zone, wellbore, wellhead equipment, and flow lines [5, 6].

If at low temperatures the probability of asphaltene deposits fallout increases [6], then the increased temperature at the wells bottom (can reach ≥140°C) affects the equipment reliability. According to some data [7], the reliability of equipment with an increase in temperature can decrease by half due to the intensification of corrosion processes (the maximum carbon and low-alloy steels corrosion rate is in the temperature range from 50 to 100°C [8]). The corrosion damage problem of ESP submersible equipment is especially relevant. The course of corrosion processes is influenced by a complex of factors, such as high water cut, the presence of hydrogen sulfide and carbon dioxide in the formation fluid, and mechanical impurities. It was experimentally proven that, due to mechanical impurities, the course of corrosion is accelerated up to 2–3 times [3, 8]. Corrosion damage is often local in nature [2, 3, 9], the result of which is deep metal destruction up to the appearance of through holes.

Various ESP units are exposed to corrosion: the inner tubing surface, the outer surface of the ESP working bodies, the outer SEM surface, the cable metal sheath, and the casing. According to statistics, approximately 70% of failures due to corrosion account for submersible electric motor housings [9]. Based on the SEM's MTBF data of the Samaraneftegaz enterprises in 2013–2017, there is a tendency towards a gradual decrease in the MTBF from 601 to 503 days.

These data indicate a significant wear of electric motors and a decrease in their residual life, which leads to more frequent overhauls of equipment and a reduction in the overhaul period. Eliminating submersible motor failures while in service is a rather complicated and expensive process including equipment lifting, economic losses from well downtime, and repair or replacement of a failed SEM [10].

From the above, it is possible to make an unequivocal conclusion that the submersible motor protection from corrosion and wear is an extremely urgent task.

PROTECTION OF SUBMERSIBLE MOTORS

To reduce the corrosion impact and increase the service life of submersible electric motors, various methods of corrosion protection are used, which are classified into chemical, physical, and technological ones [2].

Chemical protection involves the use of chemical reagents—corrosion inhibitors—by pumping through an annulus or dosing through capillary tubes. The use of this method is considered ineffective [9] due to the rapid removal of the inhibitor from the formation and a rapid inhibitor film stripping from the protected metal surface at high well flow rates.

Technological methods of corrosion protection provide corrosion control and monitoring and include measures aimed at waterproofing works and reducing the flow rate, which are effective if done correctly.

However, these methods have certain risks due to their relatively short-term positive result [11].

The most widely used are physical protection methods, such as the use of SEMs in corrosion-resistant design (made of stainless steel), cathodic protection, and the application of protective polymer and metal-sprayed coatings [2, 9].

The use of corrosion-resistant equipment shows high efficiency and almost completely excludes failures due to corrosion [2]. Despite its high efficiency, the method is in little demand due to the high cost of stainless steel equipment.

Cathodic protection and the use of protective coatings are methods of electrochemical protection, the active forms of which are classified as ground and cathodic protections. Cathodic protection is carried out using ground stations and considered an effective method, but it has a rather significant drawback: a lack of data on the distribution of potentials at the well bottom [12]. The ground protection is based on the transformation of the SEM anode zone into a cathodic one by installing a protector in the SEM stem, which is made of nonferrous metal alloys and becomes an anode, diverting the electrochemical corrosion process [13].

The most widespread is passive electrochemical protection, the essence of which is the application of an anticorrosive protective coating to the equipment surface. The protective coating effectively resists the effects of the entire complex of complicating factors such as aggressive environment, mechanical wear, bacteria, salt deposits, and asphaltene deposits, and it helps reduce hydraulic losses [14].

To ensure corrosion resistance, various protective coatings are used, in particular, polymer or metallization ones [4]. The choice of a specific type of coating depends primarily on the equipment operating conditions.

Nevertheless, the use of metal-sprayed coatings is more preferable [9], since there are a number of limitations for polymer coatings, such as thermal stability, resistance to mechanical stress (which is especially important in the presence of mechanical impurities in the well), and a high degree of dependence on the coating quality and application technology [15].

APPLICATION OF METAL-SPRAYED COATINGS

The application of metal-sprayed coatings to protect the SEM housings significantly increases wear and corrosion resistance, which in turn contributes to the improvement of operational properties of products, increasing the service life and reliability and reducing the cost of their manufacture and maintenance [16].

The technology of gas-thermal spraying is one of the most common for the production of metal coatings due to its low cost when compared to other methods and the possibility of coating products of various configurations, which undoubtedly allows expanding the area of its application [16–18].

In the general case, the essence of thermal spraying consists of the formation of a directed flow of dispersed particles of the sprayed material, which ensures their transfer to the surface of the workpiece and the formation of a coating layer. There is no unified classification of methods for thermal spraying; their fundamental difference is determined by the type of energy source. Thus, the industry uses methods such as gas-flame surfacing and electric arc metal spraying, as well as plasma, detonation, high velocity oxygen fuel, and cold spraying [17–20].

The choice of the method depends on the field of application, chemical composition of the coating, substrate material, product geometry, and the required properties for the formed coating, as well as economic feasibility. Electric arc spraying (EAS) and high velocity spraying are the most widely used for SEM protection [16].

EAS is the process of melting two wires by burning an electric arc between them, dispersing the melt, and transferring particles with compressed air. This is the most effective method of thermal spraying, which makes it possible to obtain coatings with a high level of mechanical, physical, and chemical properties (adhesion, porosity, and microhardness) [16]. The main disadvantages of EAS include the possibility of overheating and oxidation of the sprayed material, the formation of coatings with a large amount of oxides and high porosity, and significant losses of the sprayed material [20].

In the high velocity oxygen fuel process (HVOF), the powder material is heated and sprayed at a high speed, 7 to 9 times the speed of sound. All coatings created by this method are characterized by high adhesion, bond strength, and low porosity [16, 18].

When choosing a particular method of application, it is necessary to take into account the main characteristics of the resulting coating. Currently, the most promising include plasma and gas-flame deposition methods, which allow the correct optimization of the spraying modes to obtain protective coatings with a sufficiently low porosity and high adhesive strength [20]. If the use of the plasma method is in less demand due to significant energy consumption, then flame spraying is characterized by simplicity, reliability, and mobility, as well as the lowest energy consumption of any technology. In this case, the optimal selected modes of flame spraying make it possible to obtain protective coatings with high rates of physical and mechanical properties, comparable to the characteristics of coatings formed by high velocity and plasma methods [20].

The most common coating materials for SEM housings on the Russian market include monel, which is applied to the metal surface by electric arc spraying and austenitic alloys based on iron, more often a chromium–nickel alloy with the addition of various components, the deposition of which can be carried out by electric arc spraying or high velocity spraying (see Table 1) [16].

Monel is a group of alloys consisting of nickel (up to 67 wt %) and copper with a small amount of other elements. Monel has high corrosion and acid resistance, resists the effects of salt water well, and practically does not corrode in neutral and alkaline solutions [20]. Despite the fact that ductile and corrosion-resistant copper is not the hardest material, its presence in the monel composition ensures the density and continuity of the coating, its corrosion resistance, and lubrication; this, in turn, leads to increased wear resistance and antifriction properties.

Iron-based austenitic stainless alloys can be used as wire or powder spray materials. The resulting coatings are characterized by high corrosion and heat resistance [20]. Adding various alloying elements makes it possible to vary the properties of the created coating.

One of the main alloying elements in stainless alloys is molybdenum. Mo is believed to have a beneficial effect on the corrosion resistance of the alloy. First, Mo changes the passive film polarity [21]; second, a positive effect of Mo when interacting with chromium is noted. The latter effect manifests itself as follows: the presence of molybdenum in the Fe–Cr based alloy contributes to the enrichment of the passive chromium film with molybdenum ions, which, occupying the empty space, makes the film more compact and, therefore, increases its protective properties [21, 22].

Table 1. Most common protective metal-sprayed coatings on the Russian market and their characteristics

Coating	Chemical composition	Application method	Porosity, %	Impregnation	Microhardness, HV	Adhesion, kg/mm^2
Monel	Ni70Cu30 + A316	Electric arc metal spraying	5–10	Epoxy	110–120 HB	3–4
Stainless steel	06Kh19N10T	Electric arc metal spraying	5–10	Optional	220–270	3–4
TSZP-VS-013 (superstainless)	200Kh28N16M5S1	HVOF	<1	Optional	500–570	>7
TSZP-VS-016	200Kh14N7S3R3	HVOF	<1	Optional	650–800	>7

Another alloying element of austenitic stainless coatings is manganese, the addition of which contributes to increased resistance to pitting corrosion. The positive effect of Mn is associated with the formation of manganese sulfides, which are, as is known, anodically polarized in the inactive region of stainless steels [21].

Another alloying, austenite-forming element is nickel, the introduction of which increases the resistance to cracking, corrosion resistance, and wear resistance. It has the highest corrosion resistance due to the formation of protective NiO_2 oxides. The addition of Ni promotes a decrease in the density of the anodic current and a change in the corrosion potential [23].

Austenitic stainless coatings provide protection for steel in aggressive environments. In [24], the following system was considered, %: 17Cr–12Ni–2.5Mo–(2–3)Si–0.03C (the rest is Fe). The powder material was applied by high velocity flame spraying. It was found that, when exposed to 3% NaCl, the coating becomes corrosion resistant for 7 days and, in the case of multilayer application (3–4 layers), the coating effectiveness against corrosion was observed for 48 days.

In addition to austenitic alloys, ferritic stainless alloys have found wide application [25, 26]. They are characterized by a low content of austenite-forming elements such as Mn and Ni. Works [25, 26] considered the effect of adding niobium on the corrosion resistance of these alloys. The introduction of a small amount of Nb contributes to an increase in the corrosion resistance of the alloy of more than two times [26], in particular, with the partial substitution of Mo. Partial substitution is explained by the higher corrosion resistance of alloys containing both of these elements (Mo and Nb) in relation to alloys with only one of them. The effect of the addition of Nb can be analyzed in terms of changes in the characteristics of the passive chromium film: when Nb ions are incorporated into the passive Cr layer, it physically changes. Electrochemically, the presence of Nb ions promotes a decrease in the current density exchange, which, in turn, decreases the corrosion rate [25, 26].

Amorphous iron-based alloys are of great interest due to the combination of various physical, mechanical, and chemical properties, such as high strength, hardness, wear, and corrosion resistance [27, 28]. Amorphous alloys are metastable materials and, as is known, do not have defects such as grain boundaries.

The most common are Fe–Cr based alloys. The influence of various elements on the properties of amorphous coatings is presented in more detail in [27, 28]. Metalloids B, C, and P are introduced mainly to create an amorphous structure of metallic glasses with improved corrosion resistance when compared with the Fe–Cr based alloy when they partially replace Fe. Additives B, C, and P in Fe–Cr alloys accelerate active dissolution to the formation of a passive film and, accordingly, lead to an increase in the amount of useful particles (such as chromium) in the passive film and, consequently, an increase in corrosion resistance.

Si additions in Fe–Cr alloys, aside from improving the ability to glass formation, have a positive effect on the composition and homogeneity of the passive chromium film, which contributes to an increase in corrosion resistance.

Aluminum (Al) based coatings are quite popular due to their high corrosion resistance in aqueous media. In addition, unlike organic coatings, aluminum provides protection not only in a complete system, but also in cases where the steel substrate is partially damaged.

Being the more active element in the electroplating range in relation to steel, the aluminum-based coating, when destroyed, provides protection, working as an evenly distributed anode [29]. Aluminum coatings were applied by electric arc spraying [29] or cold spraying [30, 31] and were characterized by a uniform homogeneous structure with low porosity and rather high wear resistance compared to the substrate metal.

The above methods of application and compositions of metal-sprayed SEM coatings are traditional and, as already noted, do not always provide a long service life of submersible oil well equipment.

Therefore, the use of more modern deposition methods and compositions of metal-sprayed coatings on SEMs is of undoubted interest. The technology of thermal spraying makes it possible to apply coatings of various compositions—from plastics to high-melting compounds [17, 32]. In the practice of spraying, in addition to single-phase materials (pure metals and their alloys, polymers, ceramics, and intermetallics), heterogeneous composite materials, as well as their mixtures, are used [17, 32]. Composite materials serve a specific function and are a combination of at least two dissimilar components with a clear interface and properties that cannot be possessed by any of the components separately [32]. It is promising to use such new composite nanostructured materials in coatings—the coatings acquire significantly better protective properties [33]. A simple energy-saving technology of self-propagating high-temperature synthesis (SHS) of high-melting compounds (carbides, nitrides, borides, etc.) and materials based on them in the combustion mode has great potential for obtaining composite and nanostructured coatings [34, 35]. Nanostructured coatings can be quite expensive, but using, for example, resource-saving SHS technology can make them quite cost-effective. The industrial application of nanostructured coatings is quite feasible, since a SEM body has a simple, cylindrical shape. One effective way to reduce the friction coefficient while maintaining high hardness and wear resistance is developing nanocomposite coatings, which, along with the solid phase of carbides and transition metal nitrides, contain a "soft" phase that plays the role of a solid lubricant or promotes the formation of self-lubricating phases during heating: silver, gold, molybdenum diselenide, calcium phosphide, carbon, etc. [36].

The most recent achievements include the development of modern functional and intelligent, so-called *smart*, coatings for the enhanced corrosion protection of metal substrates [37].

Particular attention is paid to the self-healing of coatings based on polyfunctionality by encapsulating corrosion inhibitors, antifouling agents, and additives that provide superhydrophobic coating surfaces, as well as by the chemical modification of hybrid coating matrices. It is obvious that the development and application of the above modern coatings can significantly increase the resistance of SEMs to the wear and service life of submersible oil-well equipment.

DESTRUCTION MECHANISMS OF METAL-SPRAYED COATINGS AND OPERATION RESULTS

The mechanisms of destruction of protective metal-sprayed coatings with a large number of illustrations are considered in detail in [38]. According to the results of studies carried out on SEM damaged housings, the main reasons for the destruction are ranked into several groups:

Mechanical damage. Mechanical damage is a violation of the continuity of the coating in the form of a deep scratch directed along the motor housing. Damage to the coating, depending on the intensity, leads to the "exposure" of the metal and its dissolution when interacting with an aggressive environment by electrochemical corrosion. In addition, mechanical damage to the coating adversely affects the coating properties, reducing the barrier properties and penetration of an aggressive environment to the base metal, with its subsequent corrosive destruction.

Abrasive wear. Abrasive wear of the electric motor coating is accompanied by a change in color and erasure of the coating areas with the formation of local spots of corrosion damage. The abrasive wear of the coating occurs as a result of scratching or cutting exposure to wellbore fluid solid particles. The result of such an impact on the housing surface is the occurrence of corrosion spots.

Low barrier properties. Low barrier properties of the coating do not provide a full-fledged restriction of the access of an aggressive medium through the coating layer. As a result of the electrochemical interaction of the transported medium diffused through the coating layer with the SEM housing base metal, corrosive metal destruction occurs. Further, the formation and growth of corrosion products under the coating lead to an increase in internal stresses, the breakdown of adhesive bonds, and flaking.

Imperfections in application technology. The quality of the coating depends directly on the compliance with the application technology. It consists of a series of sequential operations, which should be constantly monitored to exclude possible violations. For the studied submersible electric motors, imperfections in the deposition technology can manifest themselves in the form of a local decrease in the coating thickness or its absence on hard-to-reach areas. This type of destruction is typical for refurbished SEM housings, the surface of which has already undergone corrosive destruction; as a result, it has significant unevenness. The coating will have a difference in thickness, since it will completely repeat the topography of the SEM housing surface. The hard-to-reach areas for spraying include the walls of cavities or depths, which during spraying are in the same plane with the coating.

Summarizing the above, it should be noted that, with the many advantages of the method, the use of protective coatings does not completely solve the problem of protecting electric motors from the effects of complicating factors. The most significant disadvantages of the coatings include the following:

(A) Insufficient resistance to abrasive wear arising from contact with liquid containing abrasive particles;

(B) Insufficient resistance to mechanical shocks;

(C) Higher electrochemical potential in relation to the protected metal;

(D) Violations of the application technology, manifested in the form of a local decrease in the coating thickness or its absence in hard-to-reach areas;

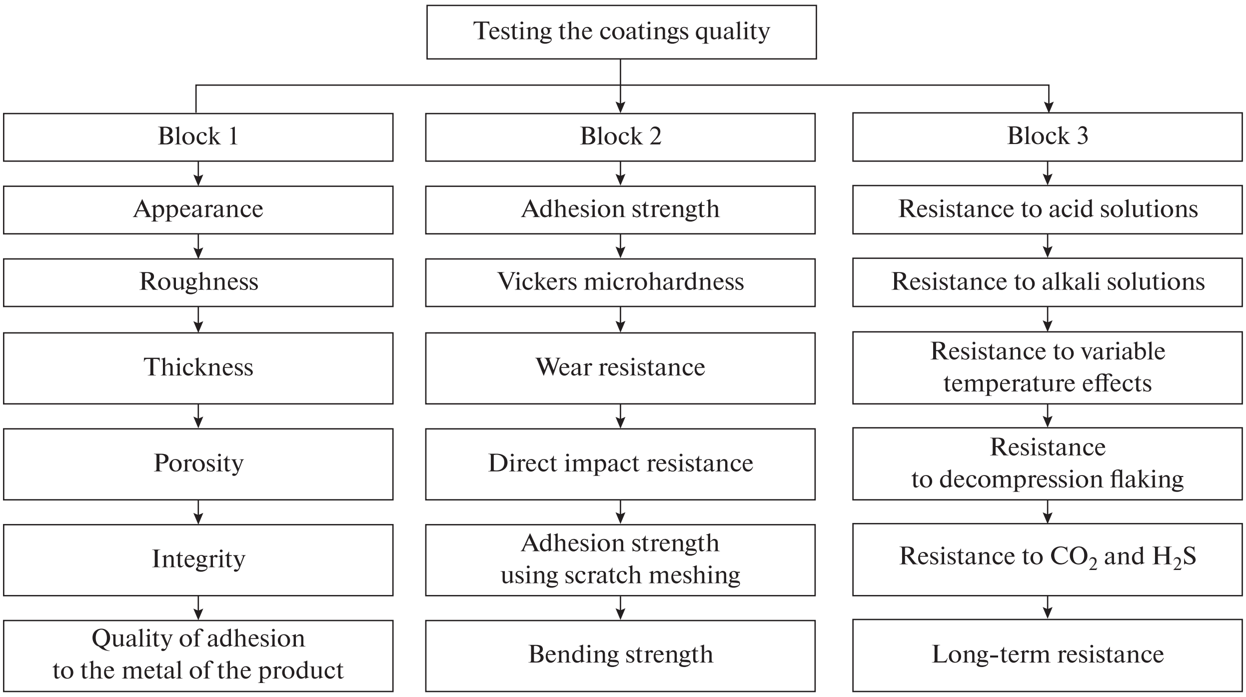

Fig. 1. Structure of test methods.

(E) Significant coating porosity, the presence of which significantly affects the quality and primarily depends on the applied method and spraying modes [16].

RECOMENDATIONS FOR ASSESSING THE QUALITY OF COATINGS FOR THE PROTECTION OF SUBMERSIBLE EQUIPMENT

The above research results were used by the authors to develop test methods and build a quality rating for anticorrosion coatings.

Recommendations for choosing a particular type of coating should be based on the results of laboratory studies, the methods of which can fully reflect the coating quality, as well as the ability to withstand the effects of destructive factors. Today, there are only a few standards that apply to thermal coatings sprayed by gas flame, plasma, and electric arc methods. These standards include a fairly narrow set of methods and are limited by requirements for coating thickness, bond strength, porosity, roughness, and corrosion resistance.

They are insufficient for modeling the mechanisms of coating destruction described above, so it is necessary to develop a comprehensive quality-assessment methodology.

The laboratory research methodology was developed in accordance with the classification of the causes of coating damage and contains three basic test blocks (see Fig.1). The complex of tests of metal-sprayed coatings is presented by methods of controlling their basic physical and mechanical properties in the initial state and after a simulation of operational effects.

The first block presents methods for controlling the technological parameters of the coating in the initial state: evaluating the appearance of the coating and its physical and mechanical properties, including roughness, thickness, porosity, continuity, and quality of adhesion to the substrate metal.

The second block of tests consists of methods that assess the resistance of coatings to external mechanical influences: the qualitative and quantitative characteristics of adhesion strength, microhardness, abrasive resistance, resistance to direct impact, and adhesion when applying a scratch mesh.

The third block of tests includes methods of accelerated testing in model environments for assessing the protective and barrier properties of metal-sprayed coatings when exposed to acids and alkalis, aqueous solutions (for a long time), variable temperatures, pressure drops, and aggressive media with a high content of CO_2 and H_2S.

Since a large set of research methods is used to assess the quality of the tested coatings, which have both quantitative and qualitative assessments, it is proposed to use the method of integral evaluation of coating properties, taking into account the results of all tests, to build a rating of the performance and reliability of coatings. At present, the developed technique is being tested; a separate article will be devoted to the obtained experimental data.

The results of an integral assessment of the coating quality, taking into account complicating factors in specific operating conditions, an increase in the service life of a submersible motor under these conditions, and the economic effect of using a submersible motor with a coating will make it possible to make a substantiated technical and economic choice of a specific SEM coating for specific operating conditions.

CONCLUSIONS

This review shows that the most effective and efficient way to protect the surface of a submersible electric motor in an oil well is the use of metal-sprayed coatings. Traditional thermal spraying technology allows the application of various types of metal-sprayed coatings. Various alloys with high corrosion resistance, wear resistance, and antifriction properties are widely used in industry. The most common coatings on the Russian market include monel and austenitic stainless-steel alloys, applied by arc metallization or high velocity spraying. Despite the many advantages of this protection method, the use of coatings does not solve completely the problem of protecting electric motors from the effects of complicating factors. The most significant disadvantages of the coatings are insufficient resistance to mechanical shock and abrasive wear, higher electrochemical potential in relation to the base metal, violations of the deposition technology, and the significant porosity of coatings. The limited number of traditionally used methods and materials is one of the main reasons for the observed shortcomings. Therefore, to solve the problem of SEM protection, significantly improving the coating properties and increasing the service life and economic efficiency, it is necessary to attract modern scientific achievements in the development of coatings to protect metal surfaces from wear and corrosion, such as

(A) expand the number of applied coating methods;

(B) increase the number of materials used for coating, create composite, nanostructured, and functional and intelligent coatings;

(C) work out a method for the integral assessment of the coating quality;

(D) develop a methodology for assessing the economic efficiency of protective coatings, taking into account all the costs of their application and income from extending the SEM service life.

The results of an integral assessment of the coating quality, taking into account complicating factors in specific operating conditions, an increase in the service life under these conditions, and the economic effect of using a coated SEM, will make it possible to make a substantiated technical and economic choice of a specific SEM coating for certain operating conditions. This review indicates the advisability of further research in this field.

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