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Influence of factors of the electric arc spraying process on the properties of coatings

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Abstract

The article discusses primary (technological factors) relating to the technology and conditions of spraying and secondary ones, which are derived from technological factors affecting the structure formation and properties of coatings. The paper examines the influence of spraying distance, dispersion of sprayed particles, wire material, etc. on the properties of electric arc coatings. Summarizing the results of research on the influence of factors of the electric arc spraying process on the structure formation and properties of coatings, the parameters of the electric arc spraying process were established, the method of preparing the surface before spraying was selected, etc. method of processing sprayed coatings.

Key words: electric arc spraying, properties, structure formation, technological factors, coatings, microhardness, density, adhesion strength

The state of the problem and the purpose of the research

In the practice of strengthening and restoring parts, the method of electric arc spraying (EAS) has become widespread as one of the most technologically advanced, productive and high-quality methods. The widespread use of electric arc spraying is facilitated by a number of significant advantages over other methods:

– high productivity of coating up to 20 kg/hour of steel, up to 10 kg/hour of aluminum;
– obtaining a coating thickness from 0.1 to 10 or more millimeters;
– wear resistance is 1.5-1.8 times higher than hardened steel 45, which is due to good oil absorption and oil retention in the micropores of the coating;
– the ability of coatings to work normally without access to lubricant until setting;
– ensuring the wear resistance of parts at the level of new ones;
– there is no deformation of parts, which is inevitable during surfacing, since during electric arc spraying there is insignificant heat input (heating temperature of the part is 100-150° C);
– simplicity and manufacturability of the process;
– the possibility of coating the surfaces of parts made of various materials (steel, cast iron, aluminum, bronze, wood, polymer, etc.);
– the dimensions of the parts do not limit the use of electric arc spraying;
– production of combined metal coatings with specified properties from various wire materials;
– low specific cost of coating application (1.4-1.8 times lower than surfacing).

The positive qualities of EAS (manufacturability, simplicity, high productivity and wear resistance, absence of thermal leads, low cost and versatility, stability of the fatigue strength of restored parts) could not go unnoticed by scientists and production workers.

However, the electric arc spraying method, like any metal coating method, also has disadvantages. The main disadvantage has always been considered to be the low adhesion-cohesive strength of the coating. The second factor limiting the use of EAS was the low hardness of the coating compared to surfacing.

Despite the large number of developments in the field of electric arc spraying (EAS), research is actively developing at the present time, and it has become focused on rational activation of the process or subsequent modification.

The aim of the work - study of the influence of factors and modes of the electric arc spraying process on the properties of coatings.

Factors influencing the structure formation and properties of coatings

The electric arc spraying (EAS) is characterized by a large number of factors that influence the structure formation and properties of coatings. It is advisable to distinguish primary (technological factors) related to technology and spraying conditions and secondary ones, which are derived from technological factors.

It is advisable to include the following as primary factors:

– factors relating to spraying modes: the magnitude of the welding current, the type, pressure and flow rate of the spraying gas, the diameter and shape of the nozzle;

– factors relating to spraying conditions: design of the blowing system; spraying distance, metallizer movement speed;

- factors relating to the sprayed material: wire diameter, chemical composition and structure of the wire, wire feed speed;

– factors relating to the preparation conditions of the sprayed surface: material, preparation method, surface roughness, heating temperature.

– factors relating to the processing of sprayed coatings.

The above primary factors determine the secondary factors that influence the kinetics and structure formation of coatings. These include: diameter, speed and temperature of particles, their degree of oxidation; degree of activation, roughness and temperature of the substrate. It should be noted that the influence of most factors on the EAS process has been studied by various researchers.

Research into the influence of electric arc spraying modes on the quality and properties of coatings

The quality of coatings and properties largely depend on the pressure of the atomizing gas and the spraying distance. Most researchers agree that increasing pressure increases coating adhesion and reduces porosity.

Studies of the influence of electric arc spraying modes on the properties of coatings show (Fig. 1) that the adhesion of the coating with an increase in the air flow rate, and, consequently, the jet flow rate, increases, and porosity decreases [1- 4]. When air flows at subsonic speed, the size of the molten particles averages 200 microns. As the air flow rate increases, 90% of the molten particle size is in the range of 30–80 µm. However, such a decrease in the size of the molten particles of the sprayed material leads to more intense burning of alloying elements from them, primarily carbon, which causes increased hardness of the coatings at subsonic air flow velocities. The content of the remaining alloying elements of the wire changes to a lesser extent with an increase in the speed of air flow from the metallizer and the arc discharge current [2].

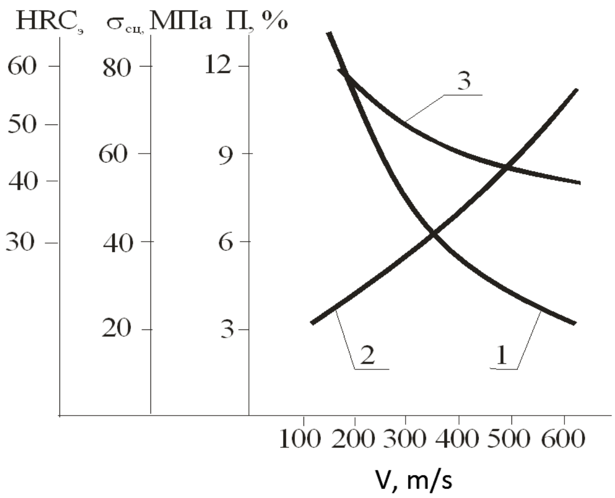


Fig. 1. Influence of air flow velocity from the nozzle (V, m/s) on the properties of coatings during electric arc spraying (EAS): 1 - porosity (P,%); 2 - adhesion strength (σ_{adh}, MPa); 3 - hardness (HRC_e)

One of the important technological factors in electric arc spraying (EAS) is the spraying distance. On the one hand, increasing the distance helps to increase the speed of particles, on the other hand, it leads to increased oxidation of the particle and a decrease in its temperature. The optimal range of spraying distance according to research [3] is in the range of 80...150 mm (Table 1).

Table 1

Properties of coatings depending on the spraying distance

Coating properties	Distance from nozzle to part, mm						
	30	50	75	100	120	200	300
Adhesion strength, MPa	15	18	19	21	22	22	19
Oxide content in the coating, %	10	12	13	15	16	25	30

By improving the design of equipment for electric arc spraying and increasing the protective energy level of the spray torch, the problem of increasing the physical and mechanical properties of coatings was solved by reducing the oxidation of dispersed metal in the spray torch and increasing the flight speed of particles. To apply coatings, devices with different blowing systems and nozzle geometries are used. Work [4] notes the advantage of devices with a closed circuit and a differential nozzle compared to an open circuit of a central nozzle. Therefore, the research in this dissertation was carried out on an EM-14 metallizer with a diaphragm nozzle.

Sprayed materials and their connection with the properties of coatings

For electric arc spraying (EAS), the use of any type of wire produced by industry is technologically possible. When spraying low-carbon unalloyed wire materials, the coating has a low level of mechanical properties. The hardness of the metal and oxides is different and amounts to 210...280 HV and 400...560 HV, respectively. The coating is characterized by high internal fragility due to the presence of a large amount of oxides (up to 20%), a high coefficient of friction f = 0.4...0.6 and low wear resistance [1, 3]. The adhesion strength to the substrate does not exceed 22...24 MPa. The porosity of the coating is in the range of 13...18%. The structure of the coatings is a layered system consisting of elongated grains (lamellas), the phase composition of which corresponds to a solid solution of chromium in α-iron, with finely dispersed inclusions of complexly alloyed boride compounds of chromium and iron.

As noted in the literature [5-9], relatively high properties of coatings using electric arc spraying (EAS) are achieved by using composite flux-cored wires. An analysis of the problems of strength and wear-resistant properties of coatings also led to the conclusion that it is necessary to use flux-cored wires for electric arc spraying (EAS). Composite flux-cored wires are most widely used (sheath made of steels Sv-08, Sv-08G2S, 30KhGSA, Steel 70, U8, U10, 20Kh13,40Kh13, 65G, filler - ferroalloys, carbides, carboborides).

These include FMI-2 flux-cored wire developed by scientists from the Physico-Mechanical Institute named after G.V. Karpenko NAS of Ukraine (Lviv, Ukraine). Protection against oxidation and high properties of coatings are achieved through the interaction of the components of the powder mixture with each other, while the processes of oxide reduction and alloying of the steel base occur. The content of ferrochrome 16-19% and aluminum 14-17% in the flux-cored wire provided a significant increase in adhesive-cohesive strength. Hardness 50-58 HRC. Coatings obtained by spraying flux-cored wires have greater hardness and wear resistance.

The practice of using flux-cored composite wires in gas-thermal spraying shows that the performance properties of coatings made from flux-cored wires are higher than those made from homogeneous ones. The advantages of flux-cored wires are determined not only by the heterogeneous structure of the coating after spraying, but also by the active interaction of the components of the powder mixture with each other during spraying and with the substrate, which contributes to an increase in the temperature of the particles, deoxidation of oxides on the surface of the substrate, and as a result, increased adhesion of the coating to the substrate.

However, our research has shown that with increasing carbon content in the sprayed composite wire, the mechanical properties of the coating increase, and the adhesion strength decreases slightly. When spraying U8 steel, the coating hardness is 360...380 HV, the adhesion strength is 18...20 MPa.

Alloyed and highly alloyed wire materials make it possible to obtain the best properties of electric arc spraying (EAS) coatings from all homogeneous wire materials. A significant increase in properties is due to the strengthening effect of alloying elements in steel.

Chromium helps, with rapid cooling, to increase the hardenability of steel, therefore the structure of coatings made of chromium steels consists mainly of martensite and its tempering products. With a significant chromium content in the original wire, $Cr_{23}C_6$ carbides are formed in the coating, as well as a small amount of austenite. Chromium significantly increases the corrosion resistance of coatings, as well as the adhesion of the coating to the lubricant. Chromium in its pure form does not affect the adhesion strength of coatings. During electric arc spraying, chromium practically does not burn out [1].

Nickel is widely used in alloys for protective coatings. It is unlimitedly soluble in iron and is a strong austenitizing element [1]. Nickel does not form its own high-hard phases in iron alloys. Its effect is to significantly increase the resistance of coatings to impact loads. With increasing nickel content, the toughness of the alloy increases with virtually no loss of wear resistance. Nickel is an expensive alloying element, so its amount in wear-resistant iron-based alloys is limited. The exception is alloys for corrosion-resistant coatings. In self-fluxing powders, nickel is used as the alloy base. In this case, high corrosion and wear resistance, as well as manufacturability of coating application, are achieved due to the formation in the M-Cr-B system of a heterogeneous structure of the eutectic type with a low melting point (less than 1000°C).

However, high-alloy wire materials are close in cost to flux-cored wire materials, however, they are inferior in efficiency (Table 2).

According to research, the diameter of the wire used during electric arc spraying (EAS) affects the conditions for the formation of a metal-air jet. In [2-4], an increase in jet turbulence is noted when the wire diameter increases to more than 1.8 mm, as well as an increase in the pressure drop in the area where the wires cross. When the wire diameter decreases to less than 1.2 mm, a deterioration in process stability is observed due to the variability of the position of the wire crossing point. The optimal range of diameters is 1.2...1.8 mm.

The influence of the method of surface preparation during electric arc spraying (EAS) on the adhesion strength and the effective stress concentration coefficient. Pre-treatment of the sprayed surface is necessary to ensure reliable contact of the sprayed material and the base metal by activating the surface layer of the base and removing contaminants. Preliminary surface treatment of the base metal is carried out using a variety of technological methods. At the first stage of surface preparation, degreasing is carried out to remove various contaminants. Next comes mechanical surface treatment. Among all the methods, the most productive are shot processing, sand blowing, cutting torn threads, and applying various forms of notches.

Table 2

Technical and economic characteristics of common grades of steel wire materials

Wire brand	Chemical composition	Purpose	Hardness after spraying, HV
Sv-08	C-0,08...0,1%	welding of low carbon steels	250...300
Sv-08G2S	C-0,08...0,1%, Mn-1,5...2,0%, Si-0,8...1,2%	welding of low carbon steels	250...300
Surfacing wire Np 40	C-0,37...0,42%	wear-resistant surfacing of machine parts	300...350
Surfacing wire Np 60	C-0,57...0,62%	wear-resistant surfacing of machine parts	350...400
65G	C-0,63...0,68%, Mn-0,8...1,2%,	wear-resistant surfacing of machine parts	350...400
U8	C-0,76...0,82%	wear-resistant surfacing of machine parts	360...400
20Kh13	C-0,18...0,22%, Cr-11...13%	wear-resistant surfacing of machine parts	360...420
Flux Cored Wire PP-TP1 (powder)	C-0,67%, Cr-3,58%, Ni-2,33%, Si-0,27%, Mn-0,42%, Al-2,08%	electric arc spraying and surfacing of tribo-joint parts	400...450
Surfacing wire NP-4 (powder)	Alloying system Fe-C-B-Cr	electric arc spraying and surfacing of tribo-joint parts	400...450

Shot treatment before spraying provides high adhesion (Table 3), increasing the endurance limit of the base metal. Therefore, during the research, the samples were subjected to shot blasting with steel chips.

Table 3

Influence of the method of surface preparation during electric arc spraying (EAS) on the adhesion strength and the effective stress concentration coefficient

Method of preparation	Strength of adhesion to the base, MPa	Effective stress concentration factor [6]
Shot processing	22	0,78
Sand blasting	20	0,91
Threading	23	1,3
Notching	22	1,29
Electrospark	23	1,08

Results of experimental studies

At the first stage of the research, the distribution of particles obtained by spraying flux-cored wire into fractions was assessed (Table 4, Fig. 2).

Since the largest fractions have a minimal share in the overall distribution pattern, it would be expected that the sprayed layers would be quite dense.

The structure of the sprayed coating was a heterophase system consisting of two or more phases separated by an interface and differing in chemical composition and properties.

Table 4

Mass fraction of particles of different fractions

№	Fraction, mm	Weight, g	Mass fraction, %
1	более 0,63	0,081	0,1
2	0,63…0,40	1,204	1,52
3	0,40…0,315	1,012	1,28
4	0,315…0,20	11,930	15,14
5	0,20…0,16	11,000	14
6	0,16…0,10	22,021	28
7	0,10…0,063	21,450	27,25
8	Менее 0,063	10,012	12,7

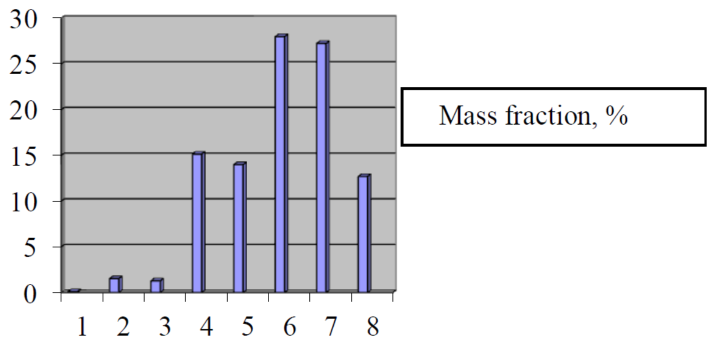


Fig. 2. Histogram of the distribution of the mass fraction of particles of different fractions

Molten particles transported by a high-speed jet of combustion products are flattened and mixed during their collision with the surface of the substrate. As a result, a specific, wavy microstructure with residual porosity is formed. The sprayed coating had a lamellar structure of crystallized particles of metal, oxides and powder filler, and the oxides are located, as a rule, along the boundaries of the lamellas (Fig. 3). As follows from the results of studying the fractional composition of particles of atomized flux-cored wire, the coatings had a fairly high density (porosity did not exceed 12-14%). Research carried out on a JSM-840 electron microscope and a MeF-3 light microscope from Reichert (Austria) showed that the powder particles included in the sprayed wire in the form of filler are fully or partially preserved. Figure 3 shows a fragment of a coating obtained by spraying FMI-2 flux-cored wire.

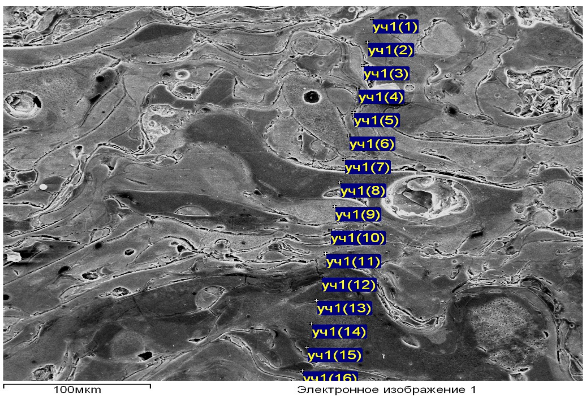


Fig. 3. Structure of the coating obtained by electric arc spraying of FMI-2 flux-cored wire

Processing of sprayed coatings

Predicting the appearance of possible structural features and physical and mechanical properties of gas-thermal coatings modified by electrical contact processing based on data obtained from electrical contact processing of loosely poured powders or layers formed by the adhesive method is impossible, which is associated with the following features of sprayed coatings:

– ultra-fast crystallization of sprayed melt droplets leads to a high concentration of crystal lattice defects (dislocations, vacancies) in the coating particles;

– the coating particles have a structure that reflects the condition of heterogeneous crystallization with the development of the front of growing crystals in the direction opposite to heat removal, i.e. perpendicular to the layer formation surface;

– the sprayed coating has pores and an extensive network of boundaries;

– when spraying coatings, there is an intense interaction of the elements included in their composition with the environment and working gases, in particular oxygen, which leads to a significant change in the phase composition and properties of the coatings.

Despite these features, the following could be expected to occur structure changes. As a result of electrical contact processing of sprayed coatings made of flux-cored wires, the formation of modified gradient structures containing a high-strength matrix phase (solid solution of carbon in (–Fe)), as well as inclusions of carbides and austenite, is possible in the surface layers.

In this case, the presence of increased amounts of austenite in the modified layer can help increase the fracture toughness and abrasive resistance of the coating [3, 10-11], and the presence of high-strength phases (martensite and carbides) in the layer should provide increased strength, as well as wear resistance of gas-thermal coatings under conditions of boundary friction and friction without lubrication. In addition, thermal force exposure at elevated temperatures can reduce the porosity of the coating and increase its adhesive resistance.

Metallographic studies showed (Fig. 4) that, as expected, as a result of thermal force exposure, the so-called "healing" of pores occurs, noted in [10, 11], the density of the coatings increased quite noticeably (porosity was 3–5%). Quantitative stereological analysis of porosity was carried out using the Genias 26 program on a certified automatic image analyzer Mini-Magiscan from Joyce Loebl, England ((Fig. 4).

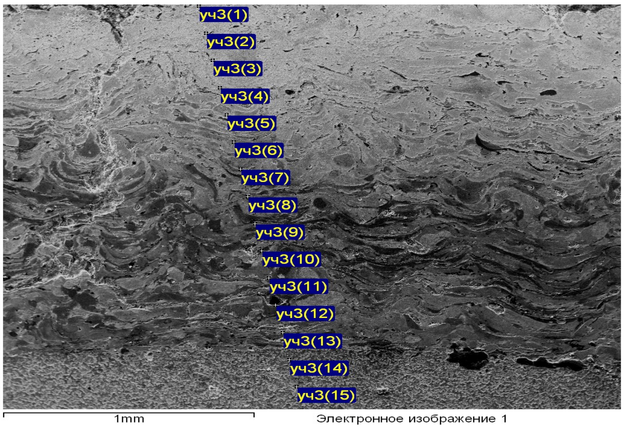


Fig. 4. Structure of the coating obtained by electric arc spraying of powder FMI-2 after electrical contact processing

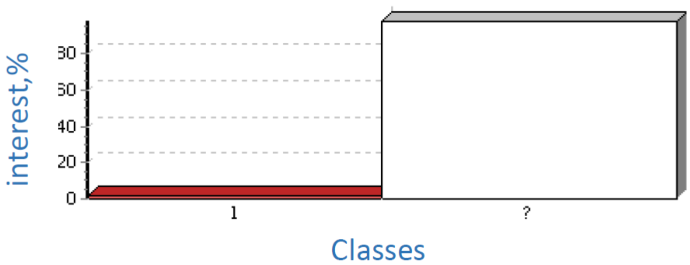
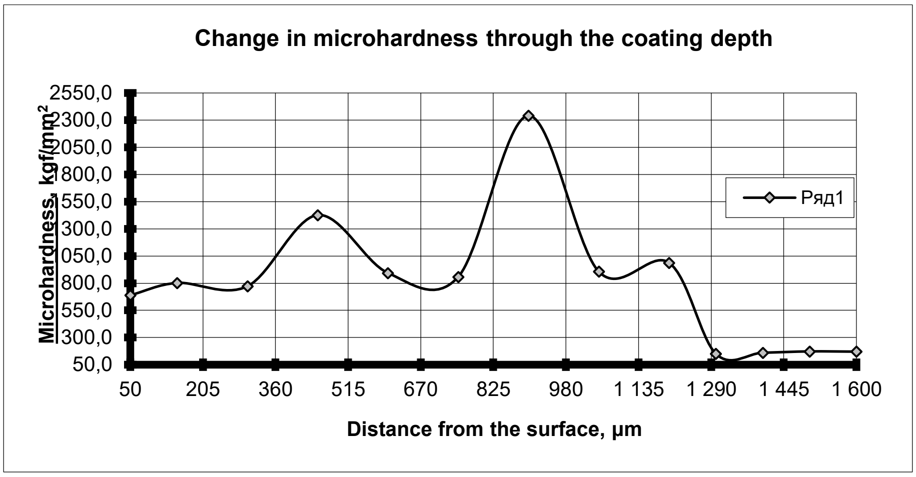
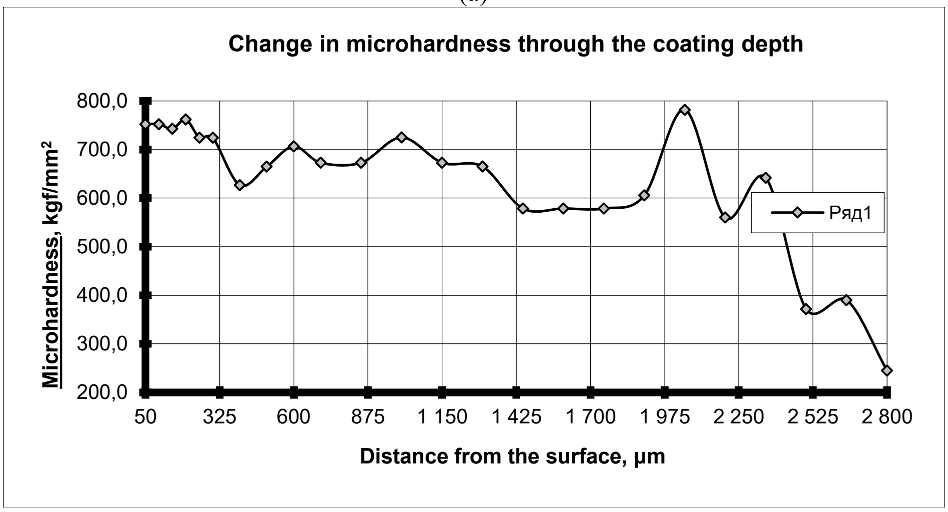


Fig. 5. Results of quantitative stereological analysis of the porosity of the coating obtained by electric arc spraying of powder FMI-2 after electrical contact treatment

Durometric studies have shown that in the process of electrical contact processing there is an increase in the hardness of the surface layer, a decrease in the microhardness of subsurface layers and an increase in microhardness in deeper layers. It has been suggested that the surface layer of the gas-thermal coating is re-hardened. Hardening leads to an increase in microhardness, and high tempering of subsurface layers contributes to their softening. In deeper layers, during electrical contact processing, the decay of retained austenite occurs, accompanied by an increase in microhardness (Fig. 6).



(a)



(b)

Fig. 6. Distribution of microhardness along the depth of sprayed coatings from the edge of the coating surface to the base, including the transition zone: a – sprayed coating made of FMI-2 flux-cored wire; b – sprayed coating of flux-cored wire FMI-2 after electrical contact treatment

Microhardness measurements were carried out using a Micromet-II microhardness tester with a load of 100 g.

Conclusions

Summarizing the results of our own research on the influence of factors of the electric arc spraying process on the structure formation and properties of coatings, and also taking into account the literature data, we established the following parameters of the EDS process during the research:

– current strength – 160...180 A;
– compressed air pressure – 0.5...0.6 MPa;
– spraying distance – 100...130 mm;
– diameter of the wire used – 1.6...2 mm;
– nozzle hole diameter – 7 mm;
– surface preparation method before spraying – shot blasting;
– method of processing sprayed coatings – electric contact.

References

1. Kharlamov Yu.A. Thermal spraying of coatings and ecological compatibility of production, operation and repair of machines. *Heavy engineering.* №2. 2000. P. 3-10.

2. Vilage B., Rupprecht K., Pokhmurskaya A. Features of gas-thermal spraying with flux-cored wires. *Automatic welding.* №10. 2011. P. 26-30.

3. Brusilo Yu.V. Choice of equipment for hardening and restoring parts of piston engines by arc spraying. *Aerospace Engineering and Technology.* Kharkiv: №4 (71), 2010. P. 38-42.

4. Matveishin E.N. Deposition of layers with high adhesion strength by methods of arc metallization. *Automatic welding*. 8. 2000. P. 20-22.

5. V.I. Pokhmursky, M.M. Student, V.S. Pikh Protective and restorative electric metallization of coatings from cored wires. *New processes and equipment for gas-thermal and vacuum coating:* Coll. of papers *"Electric welding"*. Kyiv: 1990. P. 66 - 69.

6. Student M.M. Development of old and new electrometallic coatings to cover powder darts: Thesis. Lviv: 1998. 18 p.

7. Pohmurskij V. I., Student M. M., Dovgunyk V. M. i dr. Poroshkovye provoloki sistem FeCrB+Al i FeCrB+Al+C dlya elektrodugovoj metallizacii. *Avtomaticheskaya svarka*. 2002. № 3. S. 32-35.

8. V. I. Pohmurskij, I. I. Sidorak, M. M. Student. Opyt primeneniya poroshkovyj provoloki FMI-2 dlya elektrometallizacionnogo naneseniya vosstanovitelnyh pokrytij. *Avtomaticheskaya Svarka.* 2002. №2. S. 3-4.

9. Pokhmurska G.V., Dovgunik V.M., Student M.M. Wear resistance of laser-modified electric arc coatings from cored wire FMI-2. *FKhMM* № 4. 2003. P. 61-64.

10. L.A. Lopata, N.A. Medvedeva, T.M. Tunik, S.G. Salii Improvement of sprayed coatings. *World of Engineering and Technologies.* 8 (54), 2005. P. 54-56.

11. Ageev M.S., Volkov Yu.V., Chigrai S.L. Protective and hardening coatings in ship building and repair. *Science Bulletin KhDMA.* Kherson: №2 (13). 2015. P.110-124.

Лопата О.В. , Лопата В.М. , Качинська І.Р., Забойкіна Н.П. Вплив факторів електродугового напилення на властивості покриттів

В статті розглянуті первинні (технологічні фактори), які стосуються технології і умов напилення і вторинні, які є похідними від технологічних чинників, що впливають на структуроутворення і властивості покриттів. В роботі досліджено вплив дистанції напилення, дисперсності розпилюємих частинок, матеріалу дроту та ін. на властивості електродугових покриттів. Узагальнюючи результати досліджень по впливу чинників процесу електродугового напилення на структуроутворення та властивості покриттів, були установлені параметри процесу електродугового напилення, вибрані метод підготовки поверхні перед напиленням і. спосіб обробки напилених покриттів.

Ключові слова: електродугове напилення, властивості, структуроутворення, технологічні фактори, покриття, мікротвердість, щільність, зносостійкість, міцність зчеплення