STUDY OF EFFECT OF ELECTRIC ARC SPRAYING MODES ON STRUCTURE AND PROPERTIES OF PSEUDOALLOY COATINGS

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A study of effect of electric arc spraying conditions on structure and properties of steel–copper pseudoalloy coating was performed. A method of multifactor experiment planning was used for determination of level of influence of spraying factors on coating characteristics. Analysis of splat specimens showed that the drops of metal are in a liquid state during collision with a basis at all studied modes of spraying. The regression equations were received which combine technological modes of spraying (rate of wire feed, voltage, consumption of compressed air, spraying distance) with hardness, content of steel and copper constituents, oxides and pores in the coating. It was determined that content of copper in total volume of the coating, obtained by spraying of steel and copper wires of similar diameter, depends on a heat input in spray consumable and makes around 35 vol.% at 0.6–1.0 MJ/kg and approximately 22 vol.% at 1.4–2.2 MJ/kg. Possible reasons of reduction of copper content are the burn-out (evaporation) and oxidation of copper in spraying process due to its reheating above melting point. The most efficient method of reduction of copper loss due to its burning out during spraying of pseudoalloy steel–copper coating is decrease of level of heating of spray particles and increase of their speed due to rise of compressed air consumption and reduction of heat input in the spray consumable. The best complex of structure and properties of electric arc pseudoalloy steel–copper coatings based on indexes of preservation of component relation (1:1), porosity (8 vol.%), level of oxidation (21 vol.%) and hardness (2700 MPa) was received in the case of spraying with 1.0 MJ/kg heat input in the wire and 126 m^3/h consumption of compressed air. 22 Ref., 2 Tables, 8 Figures.

Keywords: *electric arc spraying, pseudoalloy coatings, microstructure, porosity, oxidation, microhardness*

A process of electric arc spraying is characterized by large number of factors having effect on service properties of the coatings. Study of effect of these factors on process of coating formation is necessary in order to control the properties of coating being obtained.

Mechanical properties of the coatings, obtained by electric arc spraying, are concerned with their structure and depend on spraying modes which change coating microstructure (content of oxides and pores in the coating).

Oxides in the coating play a dual role. On the one hand, they significantly increase coating wear resistance since having as a rule higher hardness than the initial pure metals. At the same time, there is some critical quantity of oxides, exceeding of which provides stepwise reduction of coating serviceability under effect of external loads due to rise of its embrittlement [1]. Porosity in the coatings reduces the wear resistance at dry friction [2], however, pores have positive role in anti-friction coatings providing favorable conditions for preservation of oil film [3] during the friction process.

Most of the researchers agree in opinion that increase of pressure of spraying gas promotes decrease of coating porosity [4]. Raising of spraying gas pressure increases dispersion of spray consumable (aluminum, steel, copper) [5, 6] and velocity of particle movement [7]. This results in formation of more dense homogeneous structure of the coating. Change of wire feed rate, voltage on the electrodes and spraying distance have insignificant effect on size of spray particles (aluminum, steel–copper) [5]. Reduction arcing voltage results in some displacement of size of spray particles in area of smaller fractions during spraying of steel, copper or aluminum wires [6, 8, 9]. Increase of arc current from 150 up to 200 A leads to 1.5–2.0 % decrease of coating porosity [10].

However, increase of spraying gas pressure raises oxide content in the coating since reduction of size of spray particles promotes their more intensive interaction with oxygen [11]. Rising of particle diameter from 10 up to 237 μm provides

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approximately 30 % decrease of level of drops oxidation [12].

Content of oxides in the coating increases from 10 up to 40 % with rise of spraying distance from 25 to 300 mm due increase of time of particles interaction with oxygen in a jet [3].

When electric arc coatings are used as wear resistance materials, hardness which is determined by conditions of layer formation in metal spraying becomes an important property of the coating. Increase of pressure of spraying gas provides rise of hardness due to formation of denser layer [13]. The coatings from wire with low carbon content acquire hardness on account of large number of oxides [2]. When high-carbon wires are used, the hardness of the coating increases with rise of the distance up to 100 mm and then it reduces at further increase of the distance as a result of rise of pores in the coatings. Hardness of coatings increases from *HB* 193 to *HB* 207 using high-carbon wires if pressure of compressed air is risen from 3 to 7 atm. Increase of wire feed rate and current intensity, respectively, promote coating hardness decrease.

The process of melting and detachment of drops from wires of anode and cathode are not similar during the electric arc spraying [5, 14]. Difference in rates of wire melting (due to difference of melting temperatures of these materials) effects the process of asymmetric melting, formation and detachment of drops in spraying of pseudoalloy coatings using dissimilar wires. This results in formation of inhomogeneous microstructure. Study [15] showed inhomogeneity of distribution of the coating components over a deposition spot during spraying of copper and steel wires.

Uniformity of component distribution is an important characteristic in spraying of pseudoalloy coatings.

The aim of present paper is a study of effect of operating parameters of the electric arc spraying on microstructure (porosity, oxidation level, and homogeneity of component distribution) and hardness of pseudoalloy steel–copper coatings.

Experimental procedure. 2 mm diameter copper M1 grade wire and steel Sv08A grade wire were used as consumables during investigation of the process of formation of pseudoalloy coatings obtained by simultaneous spraying of dissimilar wires. The coatings were deposited using electric arc metallizator EM-14M with VDU-506 power source. A method of mathematical planning of experiment [16] was used to determine a nature of interaction between the conditions of wire spraying and structure of pseudoalloy coatings.

The following parameters were taken as variable factors: wire feed rate v_w, m/h; voltage on arc electrodes U, V; consumption compressed air V_g, m^3/h (pressure of compressed air, atm); spraying distance H, m. The choice was based on the fact that these factors have the most significant influence on structure and properties of the coatings [2, 5].

Half-replicate 2^{4-1} was used for a four-factor experiment. The conditions of experiment were brought in a planning matrix (Table 1). The values of arc power P and complexes of parameters characterizing specific consumption of energy for gas IU/V_g and wire IU/G_w heating were introduced (see Table 1) for analysis process of wire spraying. They allow determining the level of heat input in spray consumable and gas jet.

Table 1. Matrix for mathematical modeling of the experiment*

Number of experiment	Spraying parameters				Power P, kW	IU/V_g, MJ/m^3 of gas	Wire consumption G_w, kg/h	IU/G_w, MJ/kg of wire	d_{part}, μm [6]	S, m^2/kg	H/V_g, h/m$^2\cdot10^{-6}$
	w_w, m/h	U, V	V_g, m^3/h (pressure, atm)	H, m							
1	300	48	126 (7)	0.20	9.8	0.28	15.8	2.2	37	19.4	15.9
2	300	48	108 (6)	0.06	9.8	0.33	15.8	2.2	42	17.1	5.6
3	300	22	126 (7)	0.06	4.4	0.13	15.8	1.0	40	17.9	4.8
4	300	22	108 (6)	0.20	4.4	0.15	15.8	1.0	52	13.8	18.5
5	180	48	126 (7)	0.06	3.8	0.11	9.5	1.4	46	15.6	4.8
6	180	48	108 (6)	0.20	3.8	0.13	9.5	1.4	52	13.8	18.5
7	180	22	126 (7)	0.20	1.7	0.05	9.5	0.6	45	15.9	15.9
8	180	22	108 (6)	0.06	1.7	0.06	9.5	0.6	54	13.3	5.6

*Quantity of heat necessary for wire melting — 0.49 MJ/kg.

Received numerical values of IU/V_g and IU/G_w indexes refer to the limiting values of application of electric arc energy. It is assumed that in IU/V_g case it is completely used for heating of spraying gas and in case of IU/G_w for heating of spray wire. These factors are designed for qualitative evaluation of conditions of electric arc spraying process. Table 1 also shows a calculation of particle specific reaction surface S and index of time of their staying in jet H/V_g in order to estimate a process of oxidation of spray consumable particles.

Boundary conditions for the factors were chosen from the analysis of previous experiments and experience of electric arc spraying of coatings using wire consumables [17, 18]. The value of current was connected with change of wire feed rate and made 80 A at 180 m/h and 200 A at 300 m/h rate. Such factors as 90° incidence angle and 30° angle between the electrodes remained constant in addition to varying factors.

Investigation of state of the particles in moment of their collision with the basis was performed using splat-test following procedure described in [13]. Spraying of the splat specimens were made on the plates from polished stainless steel of 50 × 30 × 1 mm size by moving metallizator. Velometer of luminous objects ISSO-1 [19] was used for determination of velocity of particles in process of the electric arc spraying of wire consumables.

For microstructure investigation the coatings were sprayed over St3 specimens of 20 × 15 × × 3 mm size. The specimens were subjected to sand-blasting before spraying. Thickness of the coating made 500–700 μm.

All the experiments were carried out on modes corresponding to experiment plan. Microstructure of the coatings and external view of the splats were studied using metallographic microscope «Neophot-32». Image processing program «Atlas» was used for determination of content of components, oxides and pores in the coating. Microhardness was determined on microhardness tester PMT-3. The measurements were taken along the whole coating section.

Results of experiment. Analysis of the results was carried out considering indexes of process of heat input in gas and wire and conditions of particle interaction with gas medium (Table 2).

Study of shape of melt particles after collision with the surface (splat-test). The analysis of splats obtained by simultaneous spraying of copper and steel wires showed that the particles have a star-shaped form in all experiments (Figure 1).

Such type of splats is received from the particles being in a liquid state at a moment of collision with the basis, i.e. the particles do not solidify during in-flight at the spraying distance that is explained by short time of the flight [20]. Measurement of the particle velocity showed that their velocity makes around 100 m/s at the moment of particle collision with the basis. Time of particle staying in a jet equals 0.6–0.2 ms at spraying distance 0.06–0.20 m.

The color of copper constituent on the splats received during experiments 1 and 2 indicates its overheating that, apparently, being caused by combination of maximum heat inputs in the jet and wire (Table 2, experiments 1 and 2), resulting in heating of the metal to higher temperature. Spattering of the particles observed on splats 1, 2, 5 and 6 indicates their overheating related with the same problems.

Study of microstructure of pseudoalloy steel-cooper coatings. The analysis of coating structures obtained by simultaneous spraying of copper and steel wires showed that all the coatings are dense with obvious lamellar structure at given range of spraying modes (Figure 2). Such type

Table 2. Indexes of process of heat input in gas and wire and conditions of interaction of particles with gas medium

Number of experiment	Heat input in jet IU/V_g, MJ/m^3			Heat input in wire IU/G_w, MJ/kg				Size of specific reaction surface of the particles S, m^2/kg			Index of time of particle staying in jet H/V_g, h/m^2·10^{-6}	
	0.28–0.33	0.11–0.13	0.05–0.06	2.2	1.4	1.0	0.6	17–19	15–16	13–14	16–19	5–6
1	×			×				×			×	
2	×			×				×				×
3		×				×		×				×
4		×				×				×	×	
5		×			×				×			×
6		×			×					×	×	
7			×				×		×		×	
8			×				×			×		×

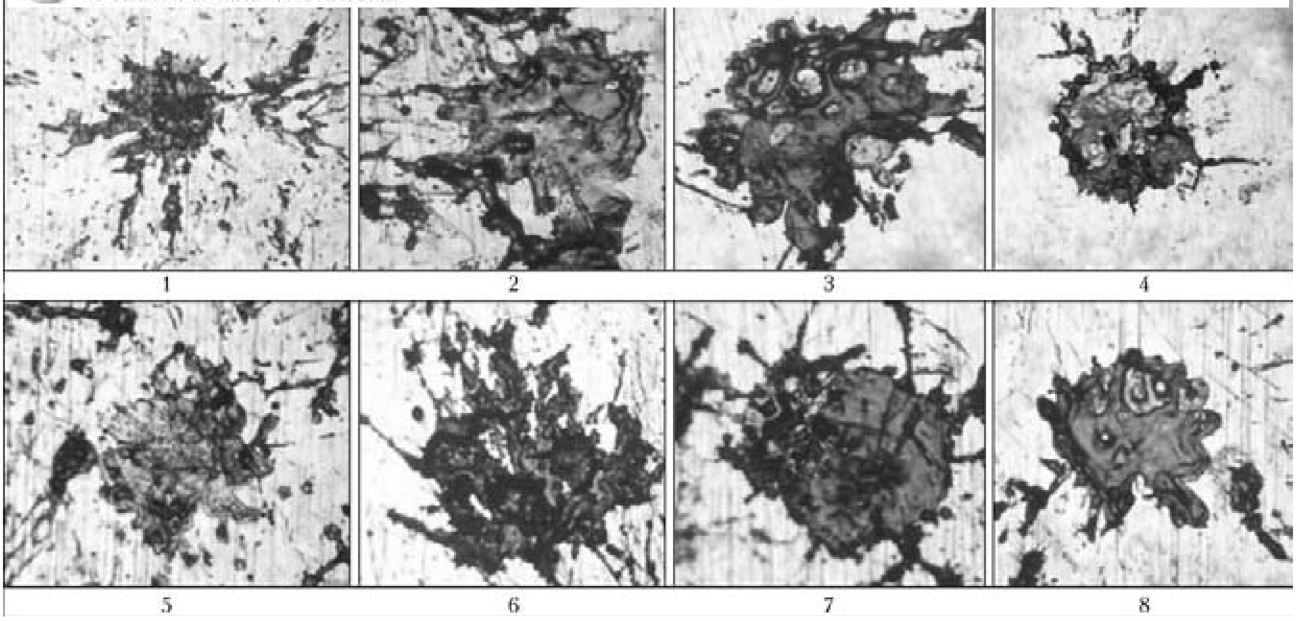

Figure 1. Splats of particles obtained by simultaneous spraying of copper and steel wires using spraying conditions according to the matrix of Table 1 (here and below 1–8 — numbers of experiments)

of structures is typical for the coating formed from the particles being in a liquid state at the collision moment and having sufficiently high velocity that corresponds to results of splats' investigation.

Table 3 shows content of components in the coating, level of oxidation and porosity.

The analysis of component content in the coatings showed a change of relative content in the coatings of copper and steel as a result of spraying. Copper content in the spray consumable using equal diameters of wires (2 mm) makes 50 vol.%. Thus, such a high values of wire heat input (Table 2, experiments 1, 2, 5 and 6) that correspond to 2.2 and 1.4 MJ/kg values provide, respectively, 36, 33, 30 and 29 vol.% content of copper in total content of copper and steel constituents. Reduction of this heat input to 1.0 MJ/kg (experiments 3 and 4) and 0.6 MJ/kg (experiments 7 and 8) increases the content of copper in total content of copper and steel constituents to 51, 48, 47 and 48 vol.%, respectively.

This phenomenon is obviously related with the fact that temperature of the molten particles during spraying can significantly exceed the temperature of copper melting [5] and achieve boiling temperature 2800 K. Since the temperatures of boiling and pressure of vapors of copper and iron are different (pressure of copper vapor (113 MPa) is higher in comparison with that of iron (13.3 MPa) [21]), increase of energy con-

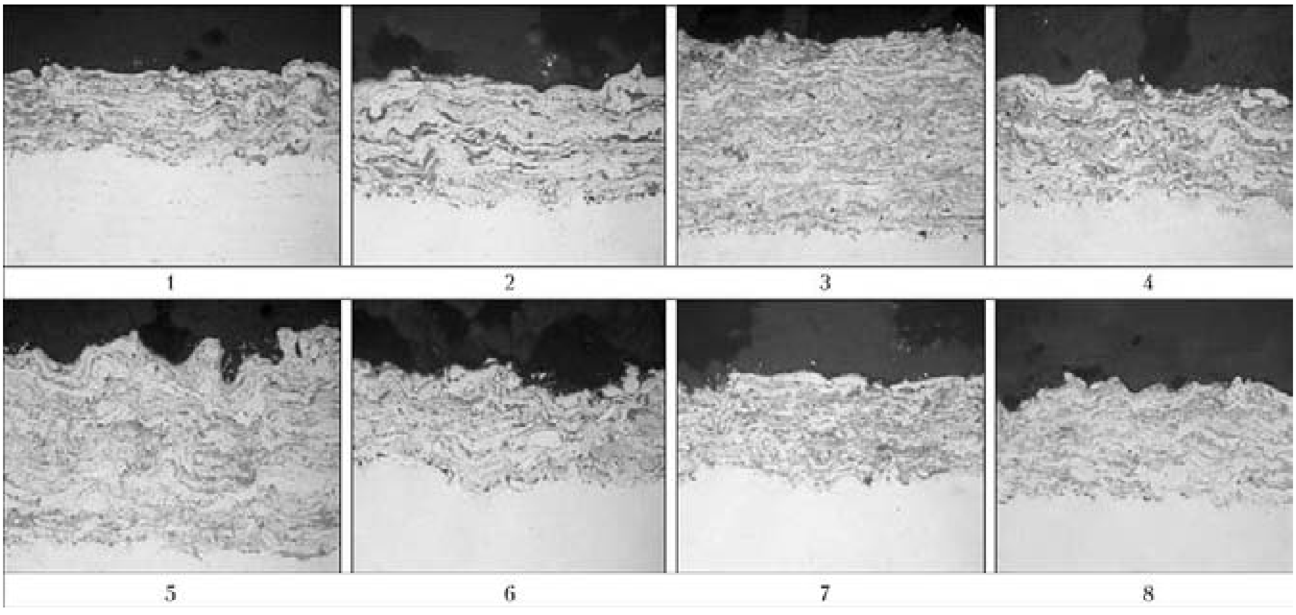

Figure 2. Microstructure (×200) of steel–copper coatings

Table 3. Content of components, level of oxidation and porosity of pseudoalloy steel–cooper coating

Number of experiment	Content of copper in coating, vol.%	Content of steel in coating, vol.%	Content of oxides, vol.%	Porosity, vol.%	Content of copper in total content of metal constituents, vol.%
1	24	42	27	7	36
2	23	47	20	10	33
3	37	36	21	8	51
4	33	36	25	6	48
5	21	49	25	5	30
6	19	46	22	13	29
7	31	35	26	8	47
8	35	38	21	6	48

sumption for wire heating (see Table 2, experiments 1, 2, 5 and 6) results in more intensive heating of copper wire during melting and, obviously, to its partial evaporation in spraying. The conditions, caused by properties of electric arc (electrodynamic forces acting in area of arc discharge) also promote transfer of copper particles in gas phase [21, 22]. Another possible reason for reduction of content of copper constituent can be the more intensive oxidation of copper in process of spraying in comparison with that of iron.

Increase of consumption of compressed air and wire feed rate lead to preservation of copper content in the coating. This can be explained by the fact that increase of compressed air consumption and, as a result, rise of speed of jet increases velocity of particles and reduces their temperature that decreases the intensity of process of copper evaporation. Regression equation, reflecting effect of process parameters on copper content in the coatings, indicates also that the most efficient method for preservation of relationship of content of components in the coating relative to the initial one is increase of the compressed air consumption and reduction of voltage for decrease of copper constituent burn out. The level of influence of spraying parameters on copper content in the coating (Figure 3) is shown by the next equation: $\%\mathrm{Cu} = 49.09 + 0.03W - 0.6U + 1.5\mathrm{V} + 0.004H$. Change of spraying distance in 0.06–0.20 m range does not provide significant effect on content of components in the coating.

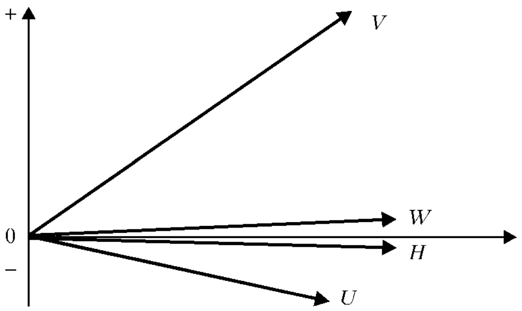

Figure 3. Level of effect of spraying factors on content of copper in coatings

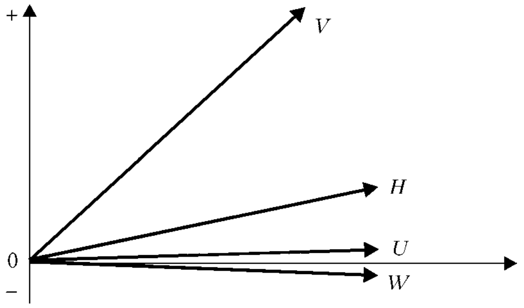

Figure 4. Level of effect of spraying factors on oxidation of coatings

The maximum content of oxides was found in the coatings sprayed using the modes with the maximum consumption of compressed air and maximum spraying distance (see Table 3, experiments 1 and 7). It is related with the fact that a rise of consumption of the compressed air results in reduction of diameter of the spray particles at wire dispersion [6]. This leads in enlargement of area of development of oxidation process. Increase of spraying distance promotes in turn the rise of time of particle staying in the jet and development of process of particle interaction with the oxygen. The level of effect of spraying factors on oxide content in the coatings (Figure 4) is represented by equation $\%\mathrm{MeO} = 2.44 - 0.002W + 0.01U + 2.75V + 0.02H$.

Figure 5 shows a dependence of oxide content in the coating on index of particle staying in the jet (H/V_g).

The results of examination of coating porosity showed that it does not exceed 13 %. As can be seen from the regression equation, the value of porosity is first of all effected by the compressed air consumption, increase of which leads to rise

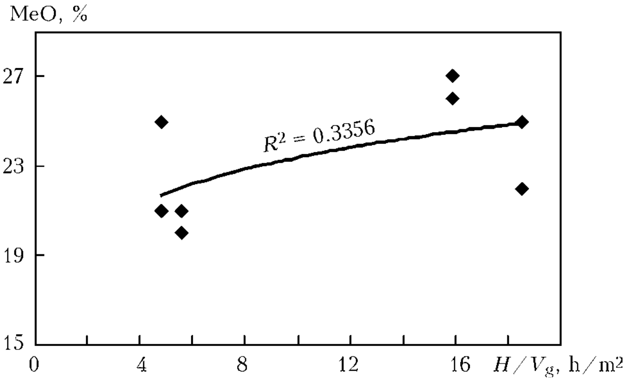

Figure 5. Dependence of coating oxidation level on index of time of particle staying in jet

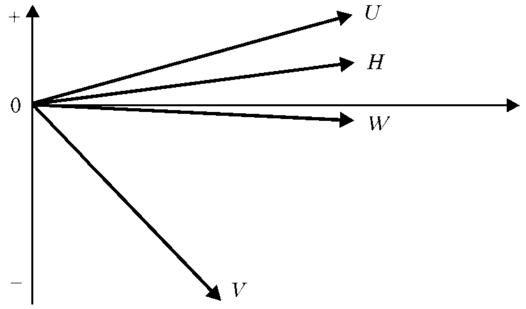

Figure 6. Level of effect of spraying factors on porosity of coatings

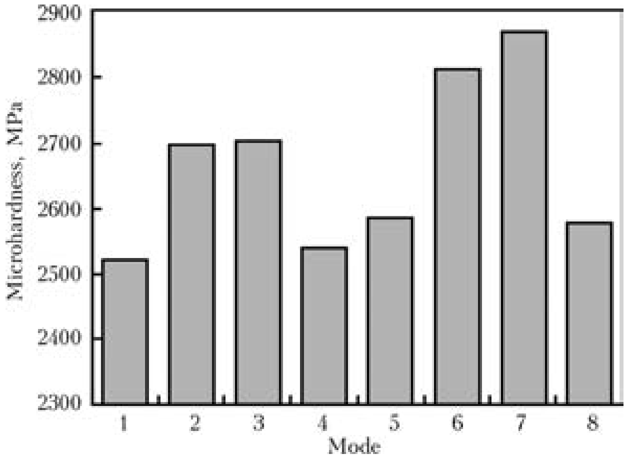

Figure 7. Dependence of microhardness of steel–copper coating on spraying mode

of particle in-flight velocity, decrease of size of spray drops, and formation of more dense coating, respectively. The level of influence of spraying factors on value of coating porosity (Figure 6) is described by equation, $\%P = 16.03 - 0.002W + 0.07U - 1.75V + 0.01H$.

Relationship of density of solid material to density of melt ($\rho_s/\rho_l = 8.93/8.03 = 1.11$ for copper and $\rho_s/\rho_l = 7.87/7.02 = 1.12$ for iron) also effects the coating porosity. Since density of melt of the coating material is less than its density in solid state, the volume of molten particles in solidification reduces that result in pore formation.

Figure 7 represents a histogram of dependence of microhardness of pseudoalloy steel–copper coating on spraying mode.

Gauging of hardness in quantity of 50 measurements was carried out along the whole cross section. The dependence of microhardness on position of measurement points was not observed. The microhardness of coatings received with different modes of spraying lies in 2500–2900 MPa range.

Received regression equations, binding spraying parameters with coating hardness show that the coating hardness increases with the rise of compressed air consumption and spraying distance. It is caused by growth of level of oxidation

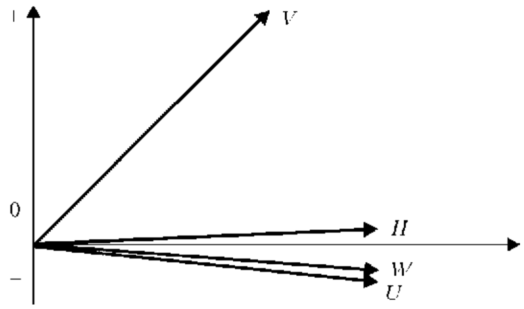

Figure 8. Level of effect of spraying factors on microhardness of steel–copper coatings

of the coating constituents at increase of these parameters and strengthening of coating material by oxide inclusions. Rising of the wire feed rate and voltage equally result in decrease of the coating hardness due to increase of heat input into the spray consumambes that can lead to their softening. The level of influence of spraying factors on microhardness of steel–copper coatings (Figure 8) is represented by regression equation $HV = 2680 - 0.8W - 0.77U + 12V + 0.324H$.

The best complex of structure and properties of electric arc pseudoalloy steel–copper coatings based on indexes of preservation of component relationship (37 vol.% Cu, 36 vol.% Fe), porosity (8 vol.%), level of oxidation (21 vol.%) and hardness (2700 MPa) was obtained in the case of spraying using wire heat input 1.0 MJ/kg and 126 m^3/h compressed air consumption (see Table 1, experiment 3). In other words, obtaining of the coating with low porosity is provided by combination of average level of input of arc energy into heating of spraying gas (air), limited intensity of heating of wire melt and increased rate of high dispersion spraying products.

Conclusions

1. Study of the process of pseudoalloy coating spraying was performed on the example of steel–copper pseudoalloy using the method of mathematical modelling of experiment. Analysis of the splats, received with applied range of spraying modes, showed that the particles in moment of collision with the basis are in the molten state and being characterized by high velocity (approximately 100 m/s). Coating structure is lamellar and consists of copper and steel components with oxide inclusions.

2. It was determined that change of heat input into the spray consumable during electric arc spraying of pseudoalloy coatings from copper and steel wires leads to variation of relationship of copper and steel constituents in the coating. Specific content of copper in relation to steel makes around 30 vol.% in spraying with 1.4–2.2 MJ/kg wire heat input and that makes

around 50 vol.% at 0.6–1.0 MJ/kg. Possible reasons for reduction of copper content are the burn out (evaporation) and oxidation of copper in process of spraying due to its overheating above the melting point. The most efficient method of reduction of copper loss resulting in obtaining of uniform component content in the pseudoalloy steel–copper coating is increase of the compressed air consumption up to 126 m^3/h and reduction of heat input in the spray consumable to 0.6–1.0 MJ/kg for decreasing of copper constituent burn out.

3. The maximum 26–27 % content of oxides was found in the coatings during spraying with 126 m^3/h compressed air consumption and 0.2 m spraying distance. It is related with the increase of dispersion of the spray consumables and rise of time of the particle interaction with oxygen. The value of porosity, first of all, is effected by compressed air consumption, rising of which from 108 to 126 m^3/h results in decrease of size of spray drops and consequently in formation of more dense coating.

4. Microhardness of received coatings lies in 2500–2900 MPa range. Received regression equations, binding spraying parameters with coating hardness, show that hardness of coating increases with the rise of compressed air consumption from 108 to 126 m^3/ h and spraying distance from 0.06 to 0.20 m. This is caused by growth of level of oxidation of coating constituents.

5. The main factor of spraying affecting the characteristics of pseudoalloy steel–copper coating is the compressed air consumption, rising of which leads to preservation of component content in the coating relatively to the initial one, reduction of porosity and increase of hardness.

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