INVESTIGATION OF DISPERSION OF DISSIMILAR WIRE MATERIALS DURING ELECTRIC ARC SPRAYING

Yu.S. BORISOV, N.V. VIGILYANSKAYA, I.A. DEMIANOV, A.P. GRISHCHENKO and **A.P. MURASHOV**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

The process of combined spraying of steel and copper wires under the electric arc spraying conditions was investigated. The effect of spraying parameters on the process of spraying of dissimilar wires was established, this making it possible to control particle size distribution of the spraying products in electric arc spraying of pseudo-alloy coatings and, hence, structure and properties of the resulting coatings. 2 mm diameter wires, i.e. copper wire of the M1 grade and steel wire Sv-08A, were used as spraying consumables. Investigations were carried out by using electric arc metalliser EM-14M. The regression equations describing dependence of the mean size of particles on the electric power, compressed air pressure and spraying distance were derived by using mathematical experimental design. It was found that the mean size of particles depends primarily on the compressed air pressure. Combining the maximal values of the power (9.6 kW) and compressed air pressure (7 atm) during spraying results in formation of particles of the minimal size: 37 μm in spraying of copper wire, 54 μm in spraying of steel wire Sv-08A, and 52 μm in their combined spraying. Combining the minimal values of the power (1.7 kW) and compressed air pressure (6 atm) leads to formation of particles of the maximal size: 54 μm in spraying of copper wire, 85 μm in spraying of steel wire Sv-08A, and 85 μm in their combined spraying. It was found that the pseudo-alloy particles consisting of particles of the steel melt with a copper shell on their surface are formed during the process of combined spraying of copper and steel wires as a result of inter-phase interaction of their melts. 24 Ref., 1 Table, 6 Figures.

Keywords: *electric arc spraying, steel and copper wire, melt dispersion, inter-phase interaction, pseudo-alloy, particle size distribution, microstructure of particles*

One of the key factors of the process of thermal spraying of coatings is size of spraying material particles. In many respects, it determines conditions of heating and acceleration of the particles, development of the process of their interaction with the environment and, eventually, shape and size of the particles forming the coating layer that are deformed at collision with the substrate surface [1, 2]. Thickness of these particles (splats) determines their cooling rate, which is related to the probability of formation of non-equilibrium structures (amorphous, oversaturated solid solutions, etc) in a coating [3]. Particle size distribution of a spraying material also affects homogeneity of properties of a coating and degree of heterogeneity of its structure.

Under conditions of using powders for thermal spraying, this factor is determined by the chosen particle size distribution of a source material. The basic difference of the wire thermal spraying method from the powder one consists in the fact that formation of a flow of the spraying material particles occurs directly during the coating deposition process in dispersion of the applied wire melt. This predetermines the importance of investigation of the dispersion process, the results of which are required to control formation of coatings and monitor their properties.

Electric arc spraying is characterised by a large number of factors allowing the values of velocity, temperature and, particularly, sizes of the spraying particles [4] and, hence, properties of the coating to be controlled.

Dispersion of the wire melts in electric arc spraying of coatings. A coating in electric arc spraying is formed from the molten metal drops moving in a carrier gas jet (Figure 1). Heating and melting of a spraying material occur due to heat of the electric arc burning between the consumable wires, i.e. electrodes, which the molten metal is formed from. The molten metal is blown off from the electrode tips, refined under the effect of gas-dynamic and electromagnetic forces, and moves in the form of drops towards the substrate surface.

The processes of formation and detachment of molten metal from the electrode tips were analysed in studies [4–11]. The authors considered the main forces acting on a molten metal drop forming at the wire tip. The molten metal at the electrode tips is kept by the surface tension forces. As the metal is accumulated, under the effect of electrodynamic forces it is pushed out to the peripheral parts of the electrodes, where detachment and transfer of the particles take place under the effect of a gas flow. The force that drives detachment of a drop depends on the velocity of the jet, whereas the force that holds the drop is proportional to its diameter and surface tension of the wire material melt. The balance of these forces can be written down in the form of the following equation [9]:

$$0.5C_d S \rho_g (W_g - W_p)^2 = \pi d_b \sigma, \qquad (1)$$

where C_d is the drag coefficient; $S = \pi d_{max}^2/4$ is the cross section area of the drop, m^2; ρ is the density, kg/m^3; σ is the surface tension, N/m; d_b is the detachment bridge, m; W is the velocity, m/s; and indices p and g refer to the drops and gas, respectively.

Changing the spraying parameters (wire feed speed, current and voltage at the electrodes, compressed air pressure) leads to changes in the wire melting mechanism. If there is a dynamic balance between the average speed of movement of the melting front and electrode feed speed, arcing is stable. In such a mode the gas flow provides evacuation and spraying of the molten metal from the electrodes up to their collision and short circuiting. Then the molten metal is again accumulated at the electrode tips, the arc column contracts, and the cycle is repeated. Along with periodic ejection of metal portions from the inter-electrode gap, there occurs also a continuous jet-like running off of the overheated metal from the electrode surfaces. This is a result of reduction of surface tension forces at high overheating of the molten metal, leading, consequently, to its inability to hold the fused layer on the electrode surfaces. Under the effect of the gas jet this fused layer is washed away from the electrode surfaces and sprayed [12].

The maximal size of drops torn off from the wire was estimated based on the condition of equality of surface tension forces and a drag force for arc metallising [13]:

$$d_{max} = 1/(W_g - W_p)\sqrt{8\sigma d_b/(C_d \rho_g)}. \qquad (2)$$

Solution of the inverse problem allows determining the required conditions, such as the velocity of the jet in spraying of a certain-diameter wire.

The experimental data [8] show that variations of the electric parameters of the process make it possible to vary not only the temperature of spraying particles, but also their size distribution. As indicated in studies [5, 6, 14, 15], the main parameters affecting the particle size distribution in arc metallising are the voltage at the arc electrodes and the compressed air pressure.

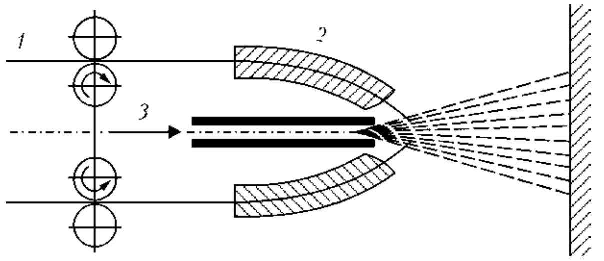

Figure 1. Flow diagram of the electric arc spraying process: *1* — wires; *2* — guides; *3* — compressed air

The degree of dispersion of the spraying material is also affected by the energy of the air jet, which in turn depends on the diameter of an air nozzle and can be expressed in the form of the following formula [5]:

$$d_{mean} = K_1(3.75/R_0 + 0.29)\sqrt{G/\gamma\mu_2} \text{ [mm]}, \qquad (3)$$

where K_1 is the size coefficient; R_0 is the radius of the air nozzle; G is the device productivity, kg/s; γ is the density of the spraying material, kg/m^3; and μ_2 is the spraying uniformity coefficient.

Physical-chemical processes occurring in molten metal during melting of the electrode by the arc, sizes of particles of the melt being sprayed, and properties of the coatings also depend on the intensity of melting of the electrodes and mass of the molten metal at their tips. Study [7] suggests formulae for approximate calculation of mass of the molten metal formed at the electrode tips in the inter-electrode gap during melting of solid and flux-cored wires. They allow for such factors of the electric arc metallising process as the arc current, electrode feed speed, frequency of molten metal ejections, and electrode diameters.

In spraying of pseudo-alloy coatings, two wires of dissimilar metals are fed to the electric arc metallisers. Therefore, the sprayed layer is a dispersed mixture of two spraying materials. When spraying two dissimilar wires, melting may occur non-uniformly because of a difference in values of the melting temperatures. No experimental investigation results are available on the character of melting of particles in simultaneous spraying of two dissimilar wires. Data on the effect of working parameters of a metalliser on the process of spraying of dissimilar wires will make it possible to define the methods to control particle size distribution of the spraying products in electric arc spraying of pseudo-alloy coatings and, hence, structure and properties of the resulting coatings.

Mathematical experimental design matrix

Mode number	Power W, kW	Compressed air pressure P, atm	Spraying distance H, mm
1	9.6	7	200
2	9.6	6	60
3	4.4	7	60
4	4.4	6	200
5	3.8	7	60
6	3.8	6	200
7	1.7	7	200
8	1.7	6	60

The present study was aimed at investigation of the process of combined spraying of copper and steel wires under conditions of electric arc metallising, as well as the effect of the process parameters on particle size distribution in the melts and microstructure of the spraying products.

Experimental procedure. 2 mm diameter wires, i.e. copper wire of the M1 grade and steel wire Sv-08A, were used as working materials for investigation of the spraying process. The process was performed by using twin-wire electric-arc metalliser EM-14M. The method of mathematical experimental design was used to study the character of relationship between the wire spraying conditions and particle size distribution [16]. The following parameters were chosen as the variable factors for optimisation: arc power, compressed air pressure, and spraying distance. The choice was based on the fact that these factors exert the substantial effect on the wire spraying process [5, 6, 10]. The experimental conditions are summarized in the experimental design matrix (Table).

Boundary conditions for the factors were chosen on the basis of analysis of previous experiments and experience with electric arc spraying of coatings by using wire materials [17–19]. In addition to the above variable factors, there were also the constant factors, such as the angle of inclination of the jet to the substrate — 90°, and the angle between the electrodes — 30°.

To investigate size and structure of the particles formed in spraying of dissimilar wires, the particles were collected by spraying of the wires in water. Then the particles were separated by using a magnetic plate.

Microstructure of the particles was examined with metallographic microscope «Neophot-32». Particle size distribution of the spraying products was measured by using image processing software «Atlas».

Results of analysis of spraying products. Figure 2 shows histograms of dependence of the mean size of particles on the spraying parameters determined in separate spraying of copper and steel wires, as well as in their simultaneous spraying. It follows from them that the degree of dispersion of sprayed copper is lower than that of steel and pseudo-alloy. This seems to be related to the fact that copper has the lowest surface tension coefficient (surface tension of copper is 1.35 N/m, and that of steel is 1.85 N/m [20]).

The following regression equations were derived as a result of mathematical processing of the measurement results. They express dependence of the particle size on the spraying conditions:

$$d_p^{mean}(Cu) = 46 - 0.31W - 0.62P + 0.004H;$$
$$d_p^{mean}(Fe) = 73 - 0.15W - 0.96P + 0.004H;$$
$$d_p^{mean}(Cu - Fe) = 73 - 0.74W - 1.21P + 0.01H.$$

Analysis of the regression equations allowed evaluating the effect of the variable factors of the process on the mean size of the particles for each of the materials.

The regression equations are indicative of the fact that it is the compressed air pressure that exerts the highest effect on the size of the parti-

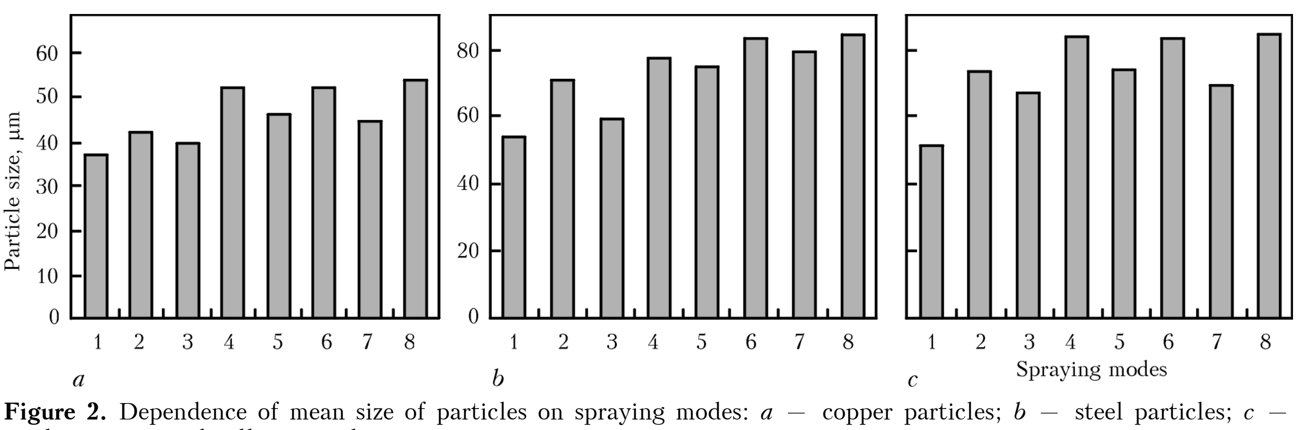

Figure 2. Dependence of mean size of particles on spraying modes: *a* — copper particles; *b* — steel particles; *c* — steel–copper pseudo-alloy particles

cles. Increasing the power and compressed air pressure leads to decrease in particle diameters. The minimal size of the particles was obtained in spraying by combining the maximal values of the power and compressed air pressure (mode 1). Combination of the maximal values of the power and compressed air pressure leads to formation of particles with the maximal sizes (mode 8).

Considering the turbulent character of the jet in electric arc spraying [13], the formed drops of the copper and iron melts may collide while moving in the jet, this determining the probability of development of the inter-phase interaction processes with phenomena of mutual mixing and formation of solid solutions in the copper–iron system. As seen from the copper–iron constitutional diagram (Figure 3), iron and copper have limited mutual solubility [21].

There are two ranges of possible interaction — at the initial stage of melting and detachment of drops from the copper and steel wire tips, and during their flight to the substrate surface.

To evaluate the possibility of interaction of particles in the spraying jet, conditional volume concentration β' of the spraying material particles in the spraying jet was calculated, and the probability of collision of the particles in the jet was estimated [22]. Conditional volume concentration β' is a ratio of the volume of the spraying material to that of the fed gas (compressed air):

$$\beta' = V_w / V_g, \tag{4}$$

where V_g is the volume of the compressed air equal to 1.2 m^3/min, and V_w is the volume of the fed wire, m^3/min, equal to

$$V_w = \pi 2 r^2 v_w, \tag{5}$$

where $r = 0.001$ m is the radius of the wire, and $v_w = 4.5$ m/min is the wire feed speed.

As shown by calculation of β' from formula (4), the conditional volume concentration of particles of the spraying material melt in the jet during metallising is $0.28 \cdot 10^{-4}$. However, it expresses the averaged distribution of the dispersed material in the jet. The distribution of particles of the material melt across the jet is non-uniform. In the first approximation it can be described by the Gaussian distribution, which is observed in the distribution of the particles that form a coating [23, 24]:

$$Y_i = Y_0 \exp - (r_i^2 / 2\delta^2), \tag{6}$$

where Y_i is the density of the flow of particles at point r_i in the jet section; Y_0 is the density of the flow of particles at the jet axis; r_i is the

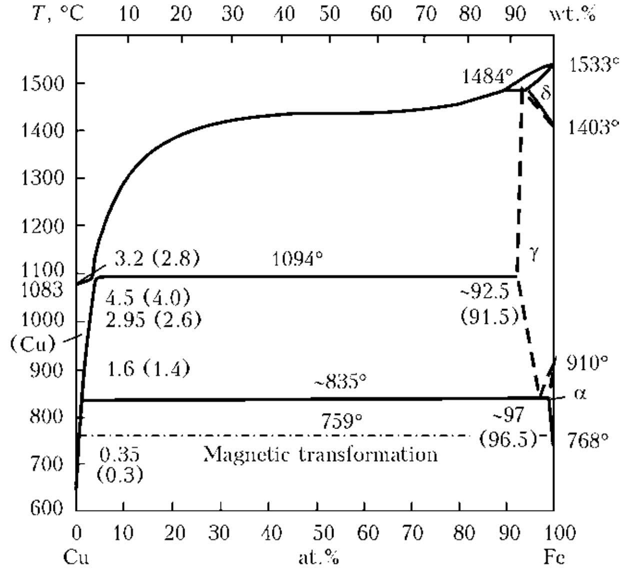

Figure 3. Copper–iron constitutional diagram

current radius of the jet section, and δ is the standard deviation.

Integration of function Y_i with respect to dr yields the total density of the flow of the dispersed material in the jet section:

$$\int_{-\infty}^{+\infty} Y_i dr = Y_0 \sqrt{2\pi\delta}. \tag{7}$$

The total density of the flow can be determined through replacing the Gauss figure by the equidimensional rectangle with base $4r_{disp}$ ($r_{disp} = \sqrt{2\delta}$ is the dispersion radius) and height equal to the average concentration of the dispersed medium in the jet.

Replacing r_{disp} by $\sqrt{2\delta}$ yields

$$Y_0 / Y_{av} = 4/\sqrt{\pi} = 2.26. \tag{8}$$

Therefore, maximal conditional concentrations β' of the particles of the material melt in the jet during spraying observed in the near-axis zone may amount to $0.64 \cdot 10^{-4}$, while the actual volume concentration of the particles of the material melt in the jet is $\beta' < 0.5 \cdot 10^{-4}$.

Calculation of the ratio of the average distance between the particles in the gas jet to their size allows evaluating the probability of collision of the particles, their coagulation in the molten state, and the resulting variation in composition and size of the spraying material particles [23]. The ratio of distance l between the particles to particle size d_p is as follows:

$$\frac{l}{d_p} = \frac{1}{\sqrt[3]{1.91\beta' - d_p}} - 1. \tag{9}$$

Figure 4 shows results of the calculation of value l/d_p at a particle diameter of 140 μm de-

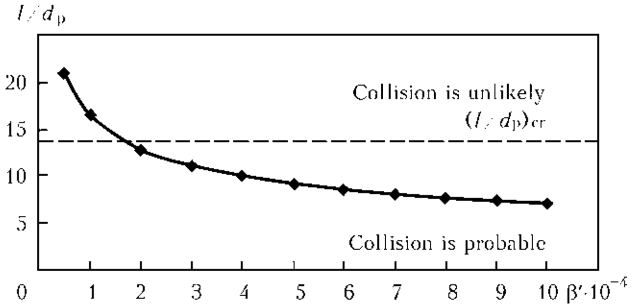

Figure 4. Dependence of inter-particle distance on concentration of dispersed phase

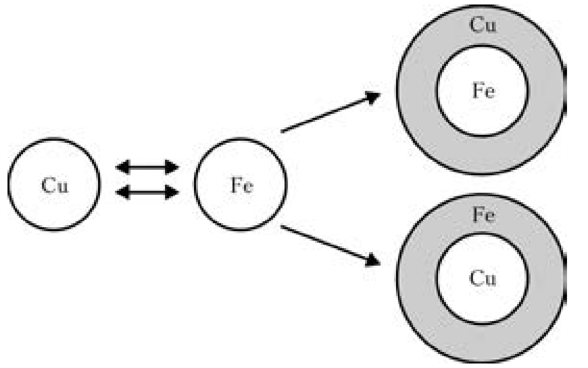

Figure 5. Types of interaction of copper and steel particles

pending on β′. It follows from these results that at the concentrations of the material particles less than $0.64\cdot10^{-4}$ the processes of collision and coagulation of the particles moving in the jet are unlikely.

Initially, the use of this procedure for evaluation of the possibility of interaction of particles within the jet showed that the particles of steel and copper during their flight within the jet should not collide and interact between each other. Nevertheless, results of magnetic separation of the entire mass of the dispersion product in combined spraying of the copper and steel wires indicated that practically all the particles of the collected powder are characterised by magnetic properties, this evidencing the presence of a magnetic material, i.e. iron, in each of them. In this connection, a necessity arose for analysis of the process of contact inter-phase interaction

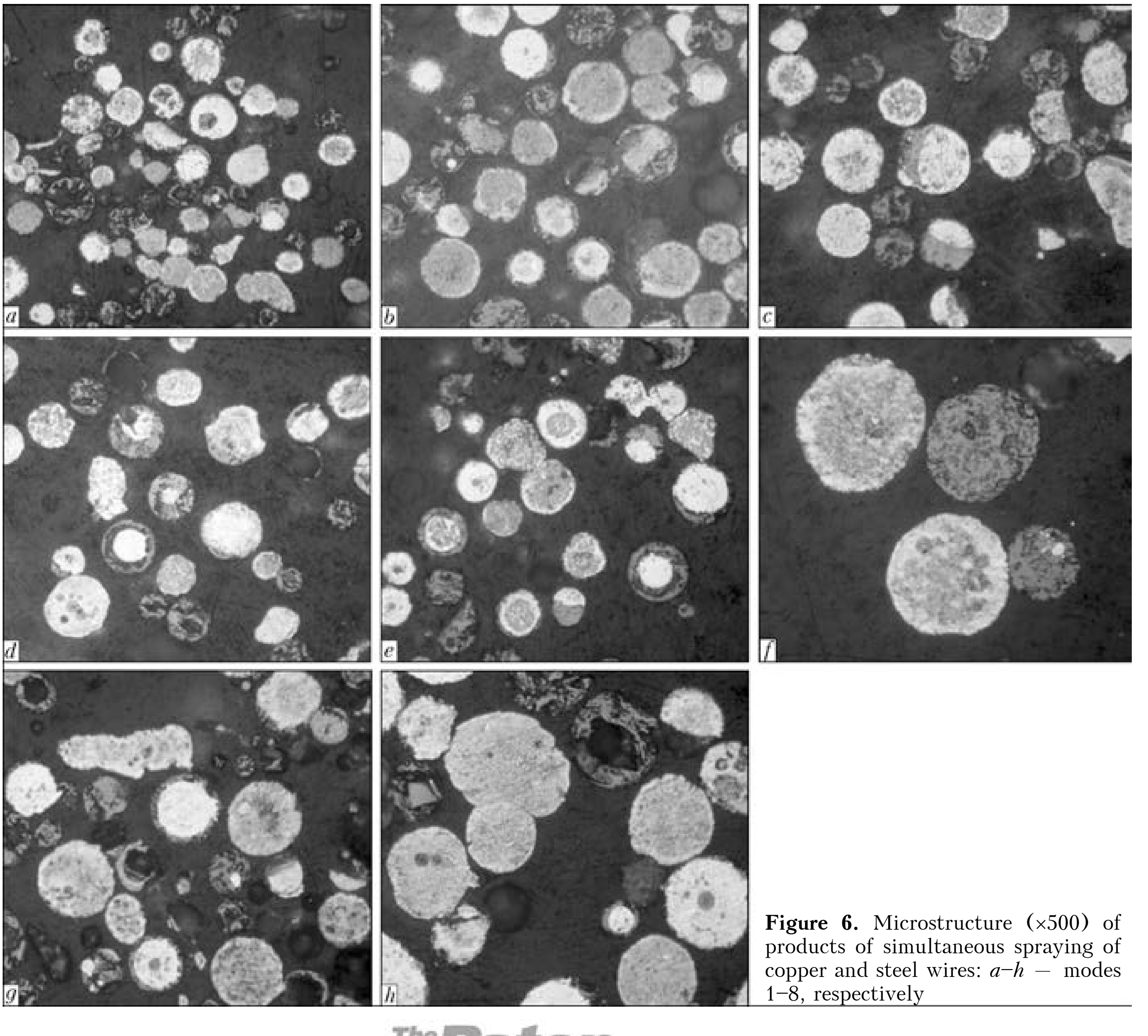

Figure 6. Microstructure (×500) of products of simultaneous spraying of copper and steel wires: *a*–*h* — modes 1–8, respectively

of particles of the copper and steel melts in case of their collision.

Calculation of the surface energy of the melt of sprayed steel and copper particles allows predicting the most probable type of contact interaction of the particles depending on their diameter. Free energy F of the surface of a liquid drop is proportional to its surface area [24]:

$$F = \sigma S, \tag{10}$$

where $S = 4\pi r^2$ is the surface area of a spherical particle with radius r, and σ is the coefficient of surface tension of the liquid.

A change in the free energy of a particle after interaction can be determined from the following formula:

$$\Delta F = F' - F, \tag{11}$$

where $F' = F_1' + F_2'$ is the energy of the particle after interaction, and $F = F_1 + F_2$ is the energy of the particle before interaction.

Figure 5 shows types of probable interactions of the steel and copper particles.

In case of capture of the steel particle by the copper one, a change in the free energy is $\Delta F = 3.6\cdot10^{-8}$ J, and in case of capture of the copper particle by the steel one this change is $\Delta F = 4.9\cdot10^{-8}$ J. Results of this calculation of the surface energy of the particles allow a conclusion that the most probable process of interaction of the steel and copper particles will occur in a direction of capture of the steel drops by the copper melt.

Analysis of microstructure of the particles showed that during the spraying process in all technological modes the copper and steel particles merge and form the pseudo-alloy particles. As seen from Figure 6, the steel and copper wire spraying products contain individual steel particles, whereas all copper particles have the form of pseudo-alloy copper–steel particles, which are the copper particles of the spherical and drop-like shapes with the fine or coarse steel particles embedded into them.

Based on the above evaluation of the probability of collision of particles in their flight within the jet, it can be assumed that the pseudo-alloy copper–steel particles form at the initial stage of melting and detachment of the melt drops from the wire tips.

Conclusions

1. The regression equations describing dependence of the mean size of particles on the values of the electric power, compressed air pressure and spraying distance were derived by using mathematical experimental design for investigation of the process of dispersion of the melts of steel and copper wires under the electric arc spraying conditions.

2. It was established that with the electric power varied within 1.7–9.6 kW, compressed air pressure — within 6–7 atm, and spraying distance — 60–200 mm, the mean size of the spraying particles in case of separate spraying of the copper wire varies within 37–54 μm, and that in case of steel wire Sv-08A — within 54–85 μm. In case of combined spraying of these wires under the said conditions the formed particles have a size of 52 to 85 μm.

3. The mean size of the particles depends primarily on the pressure of compressed air — as it increases, diameter of the particles decreases. In case of spraying by combining the maximal values of the power (9.6 kW) and compressed air pressure (7 atm), the formed particles have a minimal size: 37 μm in spraying of the copper wire, 54 μm in case of spraying wire Sv-08A, and 52 μm in their combined spraying. Combining the minimal values of the power (1.7 kW) and compressed air pressure (6 atm) leads to formation of particles with the maximal size: 54 μm in spraying of the copper wire, 85 μm in spraying of steel wire Sv-08A, and 85 μm in their combined spraying (pseudo-alloy particles).

4. It was found that electric arc spraying of copper by using copper and steel wires leads to inter-phase interaction of particles of the melts, which results in formation of a copper shell on the surface of the steel melt particles to form particles with a pseudo-alloy structure. Calculation-theoretical analysis of the interaction process shows that the most probable range of this interaction is the initial stage of the process of dispersion of the wire melts.

1. Baldaev, L.Kh., Borisov, V.N., Vakhalin, V.A. (2007) *Thermal spraying*: Manual. Ed. by L.Kh. Baldaev. Moscow: Market DS.
2. Kudinov, V.V., Bobrov, G.V. (1992) *Spraying of coatings: theory, technology and equipment*: Manual. Ed. by B.S. Mitin. Moscow: Metallurgiya.
3. Borisov, Yu.S., Korzhik, V.N. (1995) Amorphous thermal coatings. Theory and practice (Review). *Avtomatich. Svarka*, **4**, 3–11.
4. Vakhalin, V.A., Kudinov, V.V., Belashchenko, V.E. (1981) Investigation of effective efficiency of heating of electrodes and material utilisation factor in arc metallising. *Fizika i Khimiya Obrab. Materialov*, **8**, 65–69.
5. Kats, N.V., Antoshin, E.V., Vadivasov, D.G. (1966) *Spray metallising*. Moscow: Mashinostroenie.
6. Troitsky, A.F. (1960) *Principles of metallising by spraying*. Tashkent: Gosizdat UzSSR.
7. Royanov, V.A. (1990) Melting of electrodes in arc metallising. *Svarochn. Proizvodstvo*, **2**, 35–38.
8. Ageev, V.A., Belashchenko, V.E., Feldman, I.E. et al. (1989) Analysis of methods for control of parame-

ters of spraying particles in electric arc metallising. *Ibid.*, **12**, 30–32.
9. Korobov, Yu.S. (2004) Estimation of forces affecting the spray metal in electric arc metallising. *The Paton Welding J.*, **7**, 21–25.
10. Vakhalin, V.A., Kudinov, V.V., Maslennikov, S.B. et al. (1981) Process of melting and spraying of electrode material in electric arc metallising. *Fizika i Khimiya Obrab. Materialov*, **3**, 58–63.
11. Korobov, Yu.S., Boronenkov, V.N. (1998) Calculation of parameters of motion, heating and oxidation of particles in electric arc metallising. *Svarochn. Proizvodstvo*, **3**, 9–13.
12. Kuznetsov, V.D., Pashchenko, V.M. (1999) *Physical-chemical principles of coating formation*: Manual. Kyiv: NMTs VO.
13. Boronenkov, V.N., Korobov, Yu.S. (2012) *Fundamentals of arc metallising. Physical-chemical principles*. Ekaterinburg: UralGU.
14. Newbery, A.P., Granta, P.S., Neiser, R.A. (2005) The velocity and temperature of steel droplets during electric arc spraying. *Surface and Coatings Technology*, 195(**1**), 91–101.
15. Planch, M.P., Liao, H., Coddet, C. (2004) Relationships between inflight particle characteristics and coating microstructure with a twin wire arc spray process and different working conditions. *Ibid.*, 182 (**2/3**), 215–226.
16. Novik, F.S., Arsov, Ya.B. (1980) *Optimisation of metal technology process by experimental design methods*. Moscow: Mashinostroenie.
17. Kats, N.V., Antoshin, E.V., Vadivasov, D.G. et al. (1966) *Spray metallising*. Moscow: Mashinostroenie.
18. Shashkov, A.N. (1960) *Antifriction pseudo-alloys*. Moscow: Mashgiz.
19. Krasnichenko, L.V., Smolyaninov, A.I., Podkovich, E.G. et al. (1966) Complex metallising pseudo-alloys as bearing materials. In: *Application of new materials in agricultural machine-building*: Transact. Rostov-na-Donu: Risknm, 3–20.
20. (1985) *Properties of elements*: Refer. Book. Ed. by M.E. Dritsa. Moscow: Metallurgiya.
21. Hansen, M., Anderko, K. (1962) *Structures of binary alloys*. Vol. 2. Moscow: Metallurgizdat.
22. Detlaf, A.A., Yavorsky, B.M. (1973) *Course of physics. Mechanics. Fundamentals of molecular physics and thermodynamics*: Manual. Vol. 1. Moscow: Vysshaya Shkola.
23. Borisov, Yu.S. (1982) *Theoretical and technological principles of deposition of plasma coatings from composite powders*: Syn. of Thesis for Dr. of Techn. Sci. Degree. Kiev.
24. Formation of sprayed layer. *http*://www.hvof.org/theory/forming

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NEWS

Testing of Welded Vessels Using Internal Pressure at Static and Low-Cycle Loadings

On the base of Test Laboratory of the E.O. Paton Electric Welding Institute, certified by the National Body on accreditation, a hydraulic complex, put into the State Register of Ukraine, is functioning.

The complex is designed for evaluation of strength of welded structures, operating under the pressure, in the process of their designing, manufacture and service.

In the solution of this problem the procedures are used, based on the fact that the integral characteristic of suitability of any structure to service is the safety factor which is set by a single loading up to their fracture. For structures, operating at alternating loads, the procedures of tests envisage the establishment of safety factor after conductance of cyclic loadings using value and duration specified for the service conditions.

Studies of stress-strain state and strength of high-pressure vessels are carried out at internal static and low-cycle loading. Certification tests of vessels can be performed.