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CONTROL OF FORMATION OF METAL PRODUCED BY ARC METHODS OF LAYER-BY-LAYER DEPOSITION OF MATERIAL WITH FLUX-CORED WIRES

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ABSTRACT

Integrated comparative studies of the possibility of controlling formation and properties of metal by changing the electric parameters in single-layer arc deposition were conducted. The materials used were flux-cored electrode wires of 1.8–2.8 mm diameter, which were developed for three conditions of material deposition: in shielding gas atmosphere (GMAW), with open arc (SSAW) and submerged-arc (SAW). Metal part of the wires was designed so as to produce deposited metal of the type of heat-resistant tool 25Kh5FMS steel. Studies were conducted in a broad mode range: current of 150–450 A, and voltage of 20–32 V. The optimal ranges of current and voltage were experimentally determined for each material deposition method and flux-cored wire diameter, which ensure sound formation of the deposited beads, minimal penetration depth and dilution of deposited metal by base metal. Respective dependencies of the influence of current and voltage on the deposited bead geometry were plotted. Obtained experimental data can be used in the processes of additive manufacturing at selection of optimal modes of layer-by-layer arc deposition of metallic materials — wire arc additive manufacturing (WAAM) of part elements.

KEYWORDS: arc deposition, flux-cored wire, control, deposition modes, deposited metal formation, deposited bead dimensions

INTRODUCTION

It is known that in electric arc deposition of metallic materials deposited metal formation and its properties are largely determined by electric and technological parameters of the process [1].

Under the current conditions of technology development, the question arises of the possibility of using powder metallic materials for deposition and some deposition methods in additive production. We are talking about layer-by-layer arc methods of material deposition (Wire Additive Manufacturing — WAAM), which include, in particular, such technologies as gas-shielded deposition (Gas Metal Arc Welding — GMAW) or MIG/MAG Welding) or deposition by Cold Metal Transfer (CMT) method [2–9].

The process of flux-cored arc surfacing in part manufacturing in shielding gases (GMAW) or by an open arc (Self-Shielded Arc Welding (SSAW)) when solving some problems can be actually regarded as the above-mentioned additive manufacturing under one condition that machining of the thus deposited product should be absent or minimal [6].

Therefore, a priority task when studying the possibilities of application of arc surfacing methods and surfacing materials for deposition in additive manufacturing is determination of the regularities of the influence of deposition mode parameters on the geometrical dimensions and quality of deposited bead formation.

The objective of the work is experimental study of the possibility of controlling the formation and properties of metal produced by different methods of arc deposition with flux-cored wires of the same chemical composition, but of different diameter, due to variation of the electric parameters of deposition.

MATERIALS AND EXPERIMENTAL PROCEDURES

To conduct comparative studies, nine test batches of flux-cored wires of 1.8; 2.4 and 2.8 mm diameters were manufactured for deposition in shielding gas atmosphere (80 % Ar + 20 % CO_2), by an open arc (with self-shielded flux-cored wire) and by submerged arc (AN-26P flux). Metal part of the charge of all the flux-cored wires was calculated so as to obtain deposited metal of one type — 25Kh5FMS. St3 steel plates of 15 mm thickness were used as the base metal. During the experiments voltage and current were varied in a broad range of 20–23 V and 150–450 A, taking into account the flux-cored wire diameter. Deposition rate was constant in all the experiments and was equal to 20 m/h. Deposition was performed in an all-purpose unit U-653, which was connected to VDU-505 power source. The average values of current and voltage were determined using a computerized information-measurement system [10].

During the experiments, a comparative expert assessment of the quality of formation of beads deposited in one layer in one pass was performed, presence of pores and other defects was determined. Measure-

Table 1. Influence of the modes on formation of beads deposited by 1.8 mm self-shielded flux-cored PP-Np-25Kh5FMS wire

Bead number	Deposition mode		Formation quality/defects	Bead average dimensions, mm			$\gamma_{0\,av}$, %
	I, A	*U*, V		*e*	*g*	*h*	
1.1	178	20.3	Poor/Pores, wormholes	5.4	1.6	1.1	33.5
1.2	183	23.5	Satisfactory	7.2	1.4	1.9	42.8
1.3	185	25.8	Satisfactory/Pores, wormholes	9.8	1.2	2.1	50.5
2.1	212	26.3	Good/pores	10.4	1.0	1.3	53.0
2.2	218	23.4	Good	8.8	1.7	1.5	45.0
2.3	213	20.2	Poor/Pores, wormholes	6.3	2.1	1.2	35.0

Table 2. Influence of the modes on formation of beads deposited by 1.8 mm flux-cored PP-Np-25Kh5FMS wire in shielding gases

Bead number	Deposition mode		Formation quality/defects	Bead average dimensions, mm			$\gamma_{0\,av}$, %
	I, A	*U*, V		*e*	*g*	*h*	
23.1	204	26.6	Satisfactory	11.2	4.0	2.9	42.3
23.2	225	24.0	Satisfactory, narrow bead	7.4	4.8	3.2	35.5
23.3	258	23.4	Satisfactory	12.3	4.4	4.8	38.0
23.4	350	26.7	Good	16.4	4.1	5.0	53.0
23.5	317	26.5	Good	15.7	3.8	3.3	48.5
23.6	331	26.5	Good	16.8	4.0	4.8	50.0

Table 3. Influence of the modes on formation of beads deposited by submerged arc with 1.8 mm flux-cored PP-Np-25Kh5FMS wire

Bead number	Deposition mode		Formation quality/defects	Bead average dimensions, mm			$\gamma_{0\,av}$, %
	I, A	*U*, V		*e*	*g*	*h*	
29.2	245	27.9	Satisfactory	16.6	3.9	3.8	46.0
29.3	320	27.8	Good	18.9	4.2	5.5	48.5
29.4	325	27.7	Satisfactory	16.0	4.0	5.5	50.5
29.5	301	28.9	Good	20.1	3.9	4.8	48.0
29.6	311	26.8	Good	21.8	3.8	4.4	47.5

ment of width (*e*), height (*g*) and depth (*h*) of penetration of the deposited beads, as well as deposited metal dilution by base metal (γ_0) was conducted on 6–8 macrosections, cut out of the deposits. All the obtained information was entered into the Table. After that the derived data were used to plot the graphs of dependence of the respective parameters of the deposited beads on deposition modes. For example, information derived at deposition of 1.8 mm flux-cored wire on three samples by different methods is given in Tables 1–3, and characteristic macrosections of the deposited samples — in Figure 1.

EXPERIMENTAL RESULTS

The method of submerged-arc surfacing became the most widely applied in surfacing heavily worn parts.

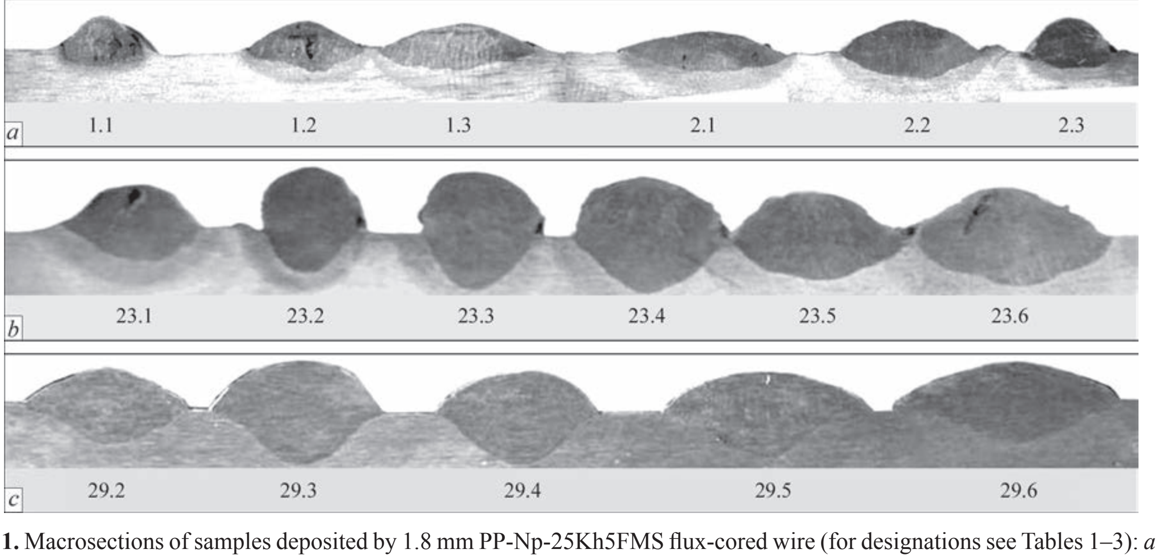

Figure 1. Macrosections of samples deposited by 1.8 mm PP-Np-25Kh5FMS flux-cored wire (for designations see Tables 1–3): *a* — by open arc; *b* — in shielding gases; *c* — by submerged-arc

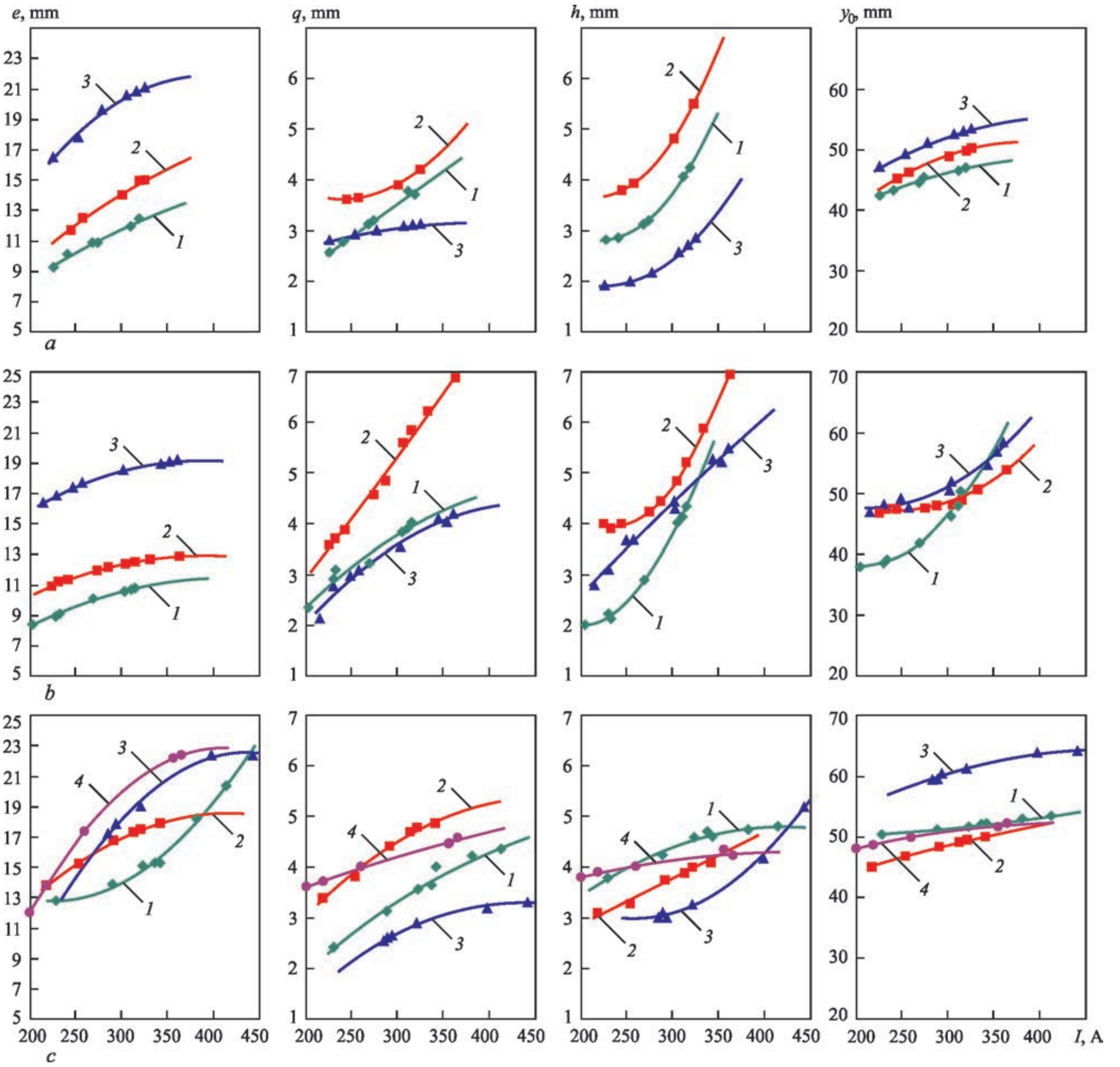

Figure 2. Current and voltage influence on dimensions of beads deposited by submerged arc with PP-Np-25Kh5FMS wire of 1.8 mm (*a*), 2.4 mm (*b*) and 2.8 mm (*c*) diameter: U = 26 V (*1*); 28 V (*2*); 30 V (*3*); 32 B (*4*)

However, application of this method to solve problems, close to additive manufacturing, for instance, restoration of flanges of wheeled vehicles, is significantly limited, because of the need for additional technological fixtures, both for containment of the liquid weld pool, and for containing the flux, which essentially complicates performance of this operation. Therefore, the information obtained under these conditions, was used as a standard, as this method allows deposition mode regulation in a broad range, while producing a well formed deposited metal. It, however, is characterized by considerable penetration depth and deposited metal dilution by base metal [11].

Graphs of dependencies of the influence of electric parameters (current and voltage) on the geometrical characteristics of beads deposited by a submerged arc, are given in Figure 2. Absence of pores or other defects in the deposited metal was noted in the entire studied range.

As one can see from Figure 2, the depth of base metal penetration becomes greater as a result of current rise, leading to increase of the effective thermal power of the arc. Voltage increase directly proportionally affects the increase of bead width, but at the same time it leads to a certain lowering of their height. It results in the bead upper part acquiring a flatter shape, the deposited metal area becoming smaller and that of the molten metal becoming larger, leading to greater dilution of the deposited metal by base metal.

Minimal value of penetration depth and deposited metal dilution by base metal, at which sound formation of the deposited metal is ensured in the studied

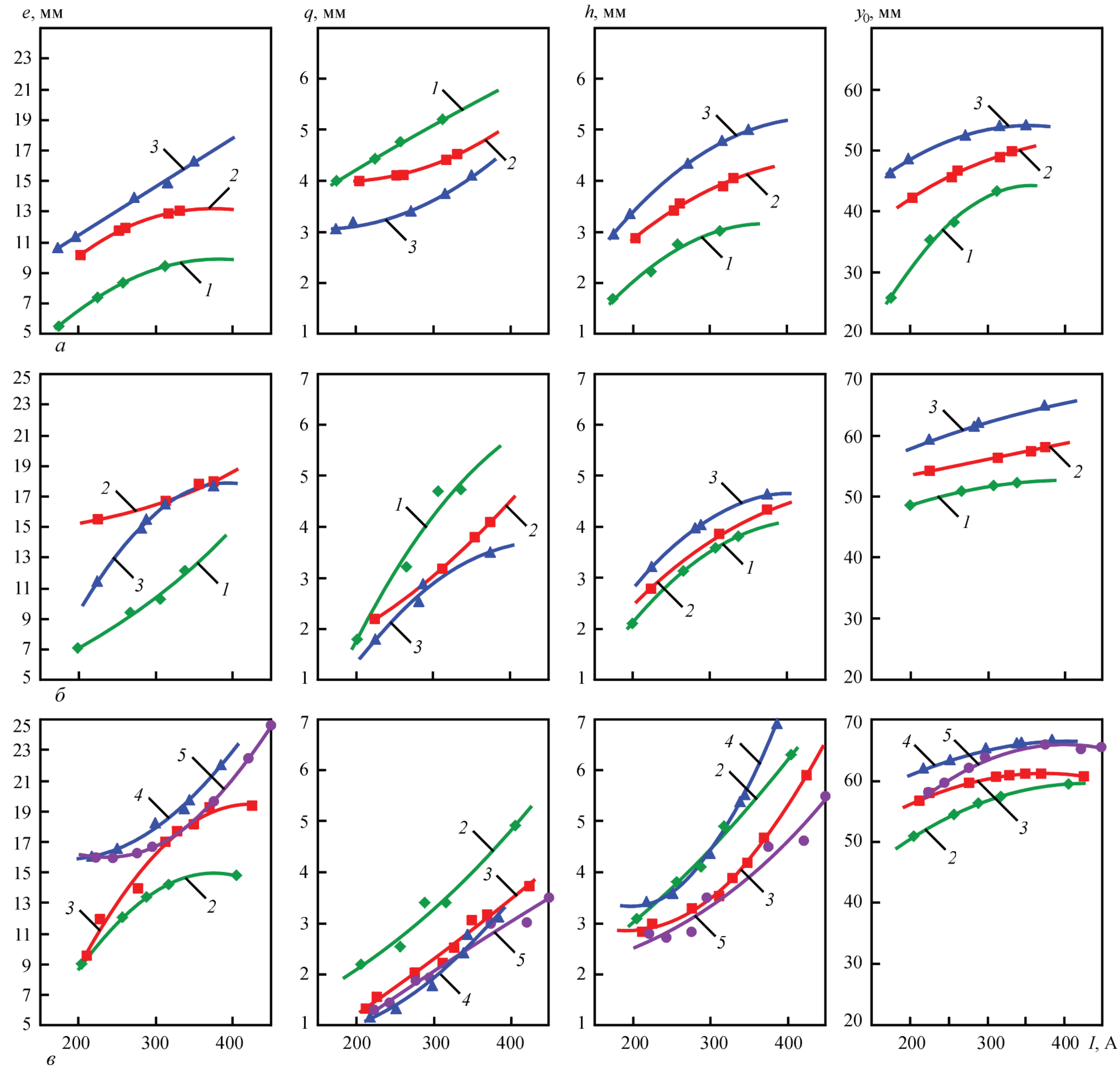

Figure 3. Current and voltage influence on dimensions of beads deposited in shielding gases with PP-Np-25Kh5FMS wire of 1.8 mm (*a*), 2.4 mm (*b*) and 2.8 mm (*c*) diameter: $U = 24$ V (*1*); 26 V (*2*); 28 V (*3*); 30 V (*4*); 32 V (*5*)

mode range at submerged-arc deposition, is equal to: 2.0 mm and 49–50 % (1.8 mm wire; $U = 30$ V; $I = 250$ A). For flux-cored wire diameter of 1.8 mm the following modes are optimal: $U = 28$–30 V; $I = 220$–300 A; here $h = 2.0$–4.8 mm; $\gamma_0 = 48$–52 %. For 2.4 mm diameter: $U = 28$–30 V; $I = 250$–350 A; here $h = 3.7$–5.4 mm; $\gamma_0 = 48$–56 %. For 2.8 mm diameter: $U = 28$–32 V; $I = 250$–400 A; here $h = 3.8$–4.4 mm, $\gamma_0 = 45$–52 %.

Application of gas shielding expands the technological capabilities, compared to submerged-arc deposition, allowing deposition on complex-shaped parts with application of different spatial positions, etc. Actually, as was said above, when minimizing machining of the deposited surfaces, this method can be used with success in additive manufacturing. Influence of current and voltage on the quality of formation and dimensions of beads deposited in shielding gas atmosphere, is shown in Figure 3.

One can see from Figure 3 that both at gas-shielded and at submerged-arc deposition, increase of current and voltage, on the whole, leads to increase of penetration depth, deposited bead width and deposited metal dilution by base metal.

Lower intensity of the influence of current and voltage on bead formation compared to submerged-arc deposition can be noted, which is attributable to lower thermal efficiency of this process through burn-out and spattering losses.

For the method of gas-shielded deposition the minimal values of penetration depth and deposited metal dilution by base metal is equal to 3.4 mm and 43–45 % (1.8 mm diameter wire; $U = 26$ V, $I = 250$ A). The optimal range of modes, in which sound forma-

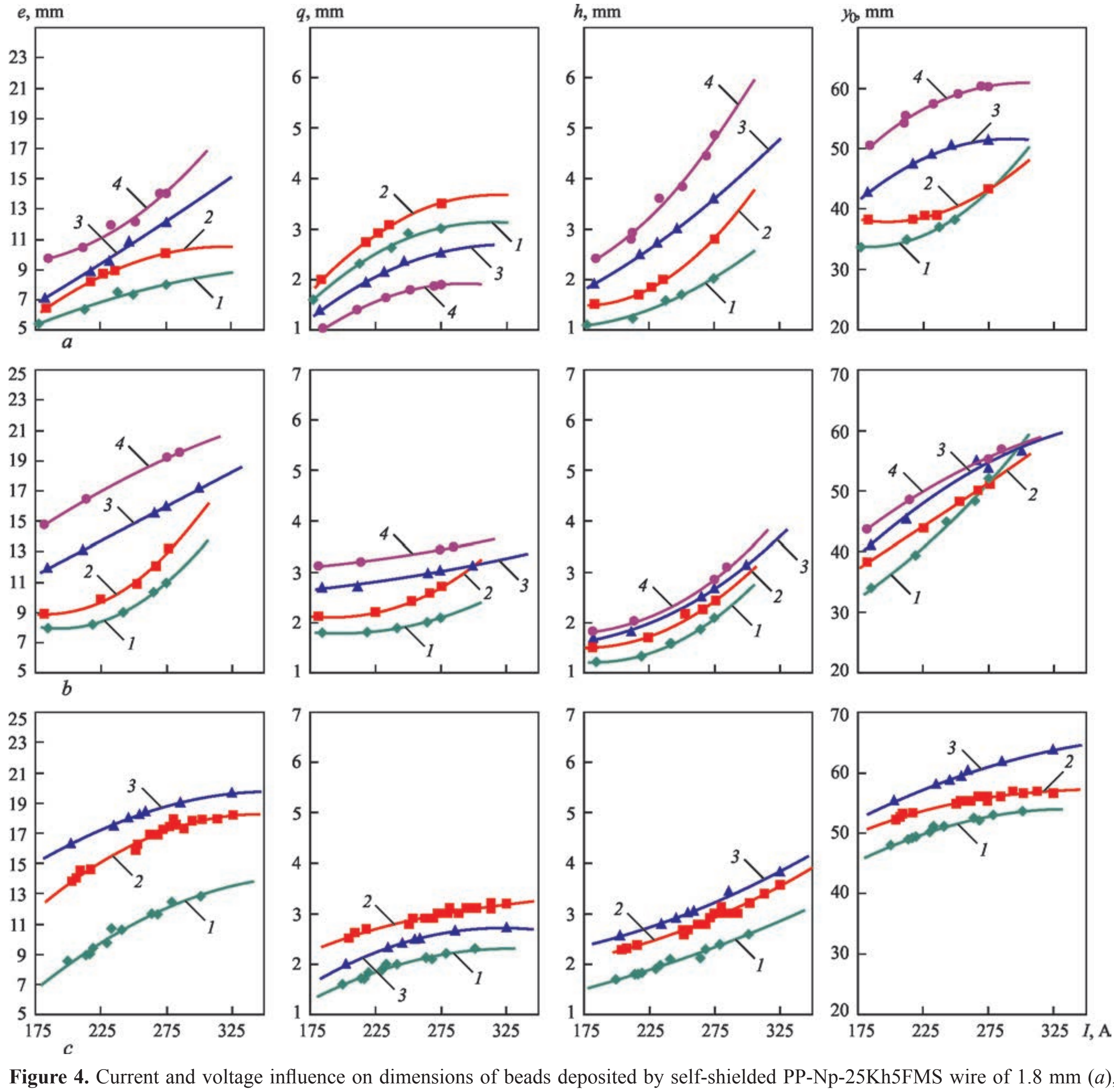

Figure 4. Current and voltage influence on dimensions of beads deposited by self-shielded PP-Np-25Kh5FMS wire of 1.8 mm (*a*), 2.4 mm (*b*) and 2.8 mm (*c*) diameter: U = 20 V (*1*); 22 V (*2*); 24 V (*3*); 26 V (*4*); 28 V (*5*); 30 V (*6*)

tion of the deposited beads is ensured for 1.8 mm wire is as follows: U = 26–27 V, I = 250–320 A; here h = = 3.4–3.8 mm; γ_0 = 45–50 %. For 2.4 mm diameter: U = 26–28 V, I = 270–350 A; here h = 3.6–4.0 mm; γ_0 = 56–58 %. For 2.8 mm: U = 27–29 V; I = 270–350 A; here h = 3.2–3.7 mm; γ_0 = 60–64 %.

Open-arc deposition (with self-shielded flux-cored wire) has a number of advantages over the above-considered deposition processes, for instance, it does not require any additional shielding of the weld pool from the environment. It, however, has one main disadvantage, which limits a wide application of this process: this is a rather narrow range of admissible deposition modes, deviation from which leads to deterioration of the quality of deposited metal formation and appearance of pores. This factor can be a problem at development of additive manufacturing technology.

Investigations of the influence of electric parameters on metal formation at open-arc deposition showed (Figure 4) that in this case a similar influence of current and voltage on the geometrical dimensions of the beads is seen, as with the previous two methods.

Increase of current value at unchanged voltage leads to an abrupt increase of penetration depth, and to formation of high and narrow beads. This is related to the intensity of liquid metal displacement from under the electrode, as a result of higher arc pressure and energy input.

Arc voltage has little effect on penetration depth, but has a significant influence on the deposited bead width and height, quality of formation and presence of defects in the deposited metal. Here, at too low or too high voltage bead formation is poor and the beads have pores. This process is characterized by a very narrow range of “optimal” modes, primarily by voltage value.

Minimal penetration depth and deposited metal dilution by base metal, at which sound formation of the deposited metal is ensured at open-arc deposition is equal to 1.6 mm and 34–37 % (1.8 mm diameter wire; U = 22V; I = 220 A).

For flux-cored wire of 1.8 mm diameter the optimal mode range is as follows: U = 22–24 V; I = = 200–250 A; here h = 1.6–2.4 mm, γ_0 = 37–40 %. For 2.4 mm diameter: U = 22–24 V, I = 210–300 A; here h = 1.6–2.4 mm, γ_0 = 38–52 %. For 2.8 mm diameter: U = 23–25 V, I = 220–300 A; here h = 2.0–2.6 mm, γ_0 = 48–54 %.

For all the above deposition methods it is necessary to note the availability of such deposition parameter ranges, in which current and voltage increase leads to a less abrupt increase of penetration depth and deposited metal dilution by base metal, or even their certain decrease. This is attributable to the ratio of current and voltage values in each case, which determine the thermal power and pressure of the arc, and rate of increase of the areas of the deposited and molten metal, accordingly. More over, the penetration depth and deposited metal dilution are influenced by current density that is why in some ranges of current values the depth of penetration for larger diameter wires can be smaller, or it can be equal to that obtained at deposition with smaller diameter wire.

CONCLUSIONS

1. Optimal ranges of current and voltage were established for arc deposition with 1.8, 2.4 and 2.8 mm flux-cored wires in shielding gases, by open arc and by submerged-arc from the view point of achieving sound formation of the deposited beads, absence of defects and minimal penetration depths and deposited metal dilution by base metal. The established dependencies can be used in development of additive manufacturing technology, based on WAAM-methods, primarily GMAW technology.

2. For the method of gas-shielded deposition (GMAW) and 1.8 mm flux-cored wire the minimal penetration depth and deposited metal dilution by base metal is equal to 3.4 mm and 43–45 % at U = = 26 V; I = 250 A; V = 20 m/h.

3. The smallest penetration depth and deposited metal dilution by base metal can be achieved at open-arc deposition with 1.8 mm flux-cored wire in the following mode: U = 22 V; I = 220 A; here h = 1.6 mm, γ_0 = 37 %. However, it is difficult to apply this method for additive manufacturing, because of the presence of a small amount of slag crust and spatter on the deposited bead surface.

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