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METHODOLOGY FOR EVALUATION OF THE WELDING AND TECHNOLOGICAL PROPERTIES OF FLUX-CORED WIRES FOR ARC SURFACING

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ABSTRACT

An analysis of existing methods for evaluating the welding and technological properties of electrode materials used in arc surfacing (welding) has been conducted. The fundamental principles for assessing the stability of the arc process have been reviewed. Key approaches to investigating the properties of electrode materials and the list of controlled parameters most frequently utilized for this purpose have been identified. It has been demonstrated that quantitative evaluation criteria are more advantageous compared to qualitative ones. Based on the analysis, a comprehensive methodology for evaluating the welding and technological properties of flux-cored wires has been developed, comprising three main components. The first component includes a visual expert assessment of the arc surfacing process and the quality of the deposited metal formation, performed using a differential scoring system. The second component focuses on evaluating the melting characteristics of flux-cored electrode wires based on experimentally determined melting rates, deposition rates, and material loss coefficients. The third component involves assessing the stability of the arc process, which is conducted using experimentally determined coefficients of variation for current and voltage fluctuations in the arc. The advantages of the proposed comprehensive methodology have been demonstrated through the evaluation of the properties of real flux-cored wires for arc surfacing. It has been established that this methodology provides more informative results compared to approaches relying solely on qualitative indices. The study confirmed that the type and granulometric composition of the metallic components in the core of flux-cored wires influence the stability of the arc surfacing process. The use of chemically purer and more homogeneous metallic granular powders in the wire core, compared to ferroalloy powders, improves the stability and productivity of the surfacing process by 15–30 %.

KEYWORDS: arc surfacing, flux-cored wire, deposited metal, welding and technological properties, surfacing stability, coefficients of variation

INTRODUCTION

It is known that flux-cored wire is a highly productive material, capable of solving a wide range of tasks, in particular those related to manufacture or restoration by arc surfacing methods of parts used in various sectors of industry [1–3].

Flux-cored wire consists of a metal sheath (from soft steel, nickel, titanium strip, etc) and core, filled with powder components. The core composition includes alloying components (ferroalloys, pure metals, carbides, borides, etc), which ensure the required chemical composition and properties of the deposited metal [1–3]. In addition to alloying elements, deoxidizing, gas- and slag-forming components are often added to the core composition, which promote shielding and refining of the molten metal. Light ionizing additives, stabilizing the arc discharge, can also be added to the core, which improves the surfacing (welding) process efficiency [1–5].

The advantages of flux-cored wires are their versatility, wide possibilities for deposited metal alloying, as well as high productivity, which ensures a significant reduction in material costs [1, 5, 6]. Due to that the flux-cored wires are used successfully in

the processes of mechanized and automatic surfacing (welding). By their operational characteristics, they are practically not inferior to solid wires, so that serial equipment can be used for surfacing [6].

Compared to flux-cored wire surfacing, however, application of solid electrode wires allows producing metal of a more homogeneous chemical composition and properties. This is due to higher stability of the deposition process in the second case.

The high stability of the surfacing process, and, thus, greater homogeneity of the deposited metal by its composition and properties are particularly important during deposition of corrosion-, gas-erosion- and wear-resistant layers on critical parts, operating in the chemical, oil and gas, metallurgical and other industries. In such cases, during selection of electrode materials, there arises the need for evaluation of their welding and technological properties, as well as studying the influence of numerous factors, among which the composition of the flux-cored wire filler (core) is of key importance.

THE OBJECTIVE OF THE WORK

is analysis of the available procedures for evaluation of welding and technological properties of electrode materials, used in surfacing (welding), as well as de-

velopment of the respective methodology for arc surfacing methods with application of flux-cored electrode wires.

ANALYSIS OF REFERENCE SOURCES

Stability of the surfacing (welding) process is one of the key parameters of welding and technological properties of electrode materials. At the same time, it is a complex and multifactorial concept, for which there is no unified standardized evaluation methodology [4, 7]. Stability depends on the parameters of the object of study. The researchers choose or develop the methodology for stability determination in each specific case, depending on the defined tasks.

Various technological measures are applied to increase the uniformity of melting of the flux-cored wire core and sheath, in order to improve the homogeneity of the obtained deposited metal. Among them are increase in the fraction of metallic powders in the core composition, selection of low-melting compositions for slag-forming components, reduction of sheath thickness, etc [3].

The welding and technological properties of electrode materials are often evaluated by visual examination of the produced samples and analysis of the quality of formation of the deposited bead or weld [8–11]. Visual examination is conducted using a magnifying glass with magnification of $\times 2$ – 5 , with recording of the controlled parameters. They include: correspondence of the geometrical dimensions of the deposited bead (or weld) to technical documentation; dimensional stability along the entire length of the controlled segment; absence of undercuts or visible defects, etc. Such a methodology, however, allows only indirect evaluation of the arc process stability.

In the opinion of the authors of [3, 4, 6], the arc process stability can be effectively evaluated using quantitative indices. The process is considered to be stable, if deviation of its parameters from the average values does not exceed the specified level. A measure of stability in this case is the parameter deviation from its average value. Dispersion, mean-root-square deviation or coefficient of variation can be used as such a measure [12].

So, in [6] the following criteria were selected, in order to determine and optimize the welding and technological characteristics of coated electrodes and welding wire: average and critical short-circuiting frequency, coefficients of variation of the respective frequency, as well as the average and maximal weight of the metal drop.

In [5, 13] devoted to welding with self-shielded flux-cored wires, the process stability was assessed by analyzing the coefficients of variation of the weld-

ing current and voltage, as well as the average time and frequency of short-circuits determined using a system equipped with a high-speed analog-to-digital converter. Slag crust separability, presence of defects and metal losses due to spattering were assessed additionally.

Welding and technological properties of the electrodes were evaluated in [14] using a comprehensive point scoring system, taking into account the following controlled parameters: ease of arc excitation, weld formation quality, degree of metal spattering, covering property and ease of slag separation and presence of defects. Arcing stability was assessed using an automated complex of diagnostics and monitoring of the welding process parameters, also converting the derived data into final points.

In [15, 16] during surfacing with flux-cored wires and strips a methodology of evaluation of the welding and technological properties was used, which is based on determination of the quality of the deposited metal formation, melting and deposition rates, coefficients of spattering losses and arc burning stability. The quality of formation was assessed by the ratio of the deposited bead width (b) to its height (h). In the opinion of the authors of the mentioned works, the greater value (b/h), the higher is the quality of formation. Stability was determined by the value of the coefficients of variation by voltage and current: they smaller they are, the more stable is the process of arc burning.

In [17] the welding and technological properties of flux-cored wire microalloyed with boron, were assessed by a complex methodology, which incorporated the following quality parameters: mode of arc excitation (light, medium, complicated); arc burning stability (stable, satisfactory, unstable); quality of the deposited bead formation (high-quality, satisfactory, poor); type and presence of defects in the deposited metal (absent, isolated, considerable quantity); quality of slag crust separation (easy, satisfactory, complicated); compliance of the chemical composition and hardness of the deposited metal with the technical requirements (compliance, non-compliance). Melting characteristics were also evaluated by quantitative characteristics: melting and deposition rates and coefficient of losses.

DEVELOPMENT OF THE METHODOLOGY FOR EVALUATION OF WELDING AND TECHNOLOGICAL PROPERTIES OF FLUX-CORED WIRES FOR ARC SURFACING

Summing up the data presented, one can state that evaluation of the welding and technological properties of electrode materials for surfacing should be

comprehensive, in order to increase the informativeness and validity of their selection. Such key parameters should be taken into account as: characteristics of electrode wire melting, presence of defects, quality of deposited metal formation, and quality of slag crust separation (if the methods of submerged-arc or self-shielded flux-cored wire surfacing are used).

In our opinion, it is rational to evaluate the quality of deposited metal formation using a differential scoring system. Application of mathematical expressions for such an assessment, based on the relationship of its parameters [15], has no practical benefit, as the deposition modes are usually selected, taking into account the requirements to ensuring the specified penetration depth, width and height of the deposited bead [1].

It is rational to perform evaluation of the arc process stability on the base of quantitative characteristics. This is particularly important with application of electrode materials with similar characteristics, when visual determination of the arc process stability is greatly complicated. The most accurate and informative assessment can be achieved by analysis of integral values, which determine the energy state of the arc process. Examples of such values are arc voltage and current, which are recorded multiple times during the process [4].

Based on the conducted analysis and results of our own experimental research [17, 18], we developed the following methodology of comprehensive assessment of the welding and technological properties of flux-cored wires for surfacing, which consists of three components.

The first component includes visual expert evaluation of the arc surfacing process and the produced deposited metal, using the differential scoring system (Table 1). The controlled parameters used by this component are as follows: mode of arc excitation, quality of the deposited metal formation, presence of visible defects, correspondence of the deposited metal chemical composition to the requirements and quality of the slag crust separation (provided the submerged-arc or self-shielded flux-cored wire surfacing method is used).

The second component contains evaluation of the melting characteristics (productivity) of flux-cored electrode wires, which is determined by the rates of melting and deposition and coefficient of losses. The melting rate (α_m) characterizes the specific (referred to one ampere of welding current) productivity of the wire melting process. The deposition rate (α_d) characterizes the specific productivity of the deposition process. Losses of electrode metal (allowing for burnout and spattering losses) are characterized by the coeffi-

Table 1. Monitored values of welding and technological properties of flux-cored wires for surfacing with point score by the differential method

Monitored parameter	Point score	Brief characterization of the parameter
Mode of arc excitation	0	Poor. Ignition not from the first touch of the electrode to the workpiece or absence of ignition
	1	Satisfactory. Ignition without electrode sticking
	2	Good. Ignition right after the first touch of the electrode to the workpiece
Quality of the deposited metal formation	0	Poor. Bead is non-uniform by width and height, surface is coarse-scaled
	1	Satisfactory. Isolated unevenness by the width or height, also at the edges, surface is finely-scaled
	2	Good. Bead is uniform, with a smooth transition to the base metal, surface is smooth
Presence of visible defects (pores, cracks, lack-of-fusion)	0	One or more cracks > 5 mm long and/or chains, clusters of pores
	1	No cracks. Isolated pores at > 100 mm distance
	2	No defects
Compliance of the chemical composition of the deposited metal with technical requirements	0	Does not comply. Deviations of the weight fraction of any element by more than $\pm 10\%$ from its specified value or deviation of the weight fraction for two or more elements by more than $\pm 5\%$ from their specified values
	1	Partial compliance. Deviation of weight fraction for any element by more than $\pm 5\%$ of its specified value or deviation of the weight fraction for two or more elements by more than $\pm 2.5\%$ of their specified values
	2	Complies. Chemical composition of the metal is in the specified range by all the elements
Quality of slag crust separation	0	Poor. After completion of the surfacing process the crust does not separate
	1	Satisfactory. Separates at partial mechanical impact
	2	Good. Separates after deposition without additional mechanical impact

cient of losses (ψ). The above coefficients are calculated using the following expressions [17, 18]:

$$\alpha_m = \frac{G_m}{It}; \quad (1)$$

$$\alpha_d = \frac{G_d}{It}; \quad (2)$$

$$\psi = \frac{\alpha_m - \alpha_d}{\alpha_m} 100\%, \quad (3)$$

where G_m is the molten metal weight, g; G_d is the deposited metal weight, g; I the welding current, A; t is the deposition time, h.

The higher the melting and deposition rates and the smaller the losses coefficient, the higher is the productivity of flux-cored wire surfacing.

The third component contains an evaluation of the stability of the arc surfacing process, which it is proposed to perform based on the dispersion of instantaneous values of arc current and voltage with their multiple recording, using the calculated respective coefficients of variation. Application of the coefficient of variation as a controlled parameter allows elimination of the influence of the scale of different samples of the derived data.

To record the mode parameters during the deposition process, it is necessary to use devices with high-speed analog-digital converters and function of saving the derived data. In our work a digital recording multimeter ANENG AN9002, fitted with a high-speed analog-digital converter, was used for this purpose. The multimeter saves measurement results in its memory in real time and allows transmitting them to other devices, using the Bluetooth communication technology.

Analysis of the derived instantaneous values of arc current and voltage, using the calculated coefficients of variation, can be performed with application of standard tools, included into the programs for mathematical analysis, such as for instance Microsoft Excel, MathLab, etc. [19]. In this work, built-in functions of mathematical analysis of Microsoft Excel program were used.

To determine the coefficient of variation, it is necessary to first calculate the standard deviation (S). For this purpose we can use the built-in function STDEV (number 1; ...), where number 1 is the first numeric argument, which corresponds to a sample from the population. Instead of the arguments separated by a semicolon, an array or an array reference can be used. STDEV function calculates the standard deviation by the following formula:

$$S = \sqrt{\frac{\sum (X - \bar{X})^2}{n-1}}, \quad (4)$$

where X is the sample mean; n is the sample size.

Then, it is necessary to determine the arithmetic mean (X) using AVERAGE (number1; ...) function, where number 1 is the first number, reference to a cell or range, for which it is necessary to calculate the mean value. Here, it should be taken into account that AVERAGE function calculates the mean value, i.e. the center of the set of numbers in the statistical distribution. There are three most common ways to determine the mean value:

1. Arithmetic mean value is calculated by adding up a set of numbers and then distributing the resulting sum by their number.

2. Median is the number, which is the middle of a set of numbers, i.e. half of the numbers have values larger than the median, and half of the numbers have values smaller than the median.

3. Mode is the number that occurs most often in this set of numbers.

At symmetrical distribution of the set of numbers, these values of evaluation of the degree of centralization are equal. At asymmetrical distribution of a set of numbers they can differ, which should be taken into account in calculations.

The coefficient of variation is known to express the extent of variation of the studied parameter, and it is determined by the ratio of mean root square deviation (S) to the mean value of parameter (X), i.e. it is calculated by the following expression:

$$V = \frac{S}{\bar{X}}, \quad (5)$$

where S is the standard (mean-root-square) deviation; X is the arithmetic mean.

For the general case it is assumed that if the value of the coefficient of variation is smaller than 33 %, the set is believed to be homogeneous, and if it is larger than 33 %, the set is heterogeneous. In practice, during determination of the arc process stability by comparing the coefficients of variation by current and voltage, the process for which these coefficients are smaller, will be more stable. The coefficient of variation is usually expressed in percent.

Moreover, during statistical analysis of the data, often it is rational to plot the histogram of a certain parameter distribution, which allows visual evaluation of the magnitude and nature of the data scatter. In Excel program the distribution histogram is a bar chart, in which each bar is a range of values (pocket), and the bar height is proportional to the number of values in it (frequency of observations). In order to construct

Table 2. Comparative evaluation of welding and technological properties of experimental wires and stability of the process of arc surfacing with experimental wires

No.	Composition of flux-cored wire core, fraction size	Mode of arc excitation	Quality of deposited metal formation	Defects	Compliance of deposited metal chemical composition	Quality of slag crust separation	Total score	Coefficients, %				
								melting	deposition	losses	variation by current	variation by voltage
1	PG-R6M5 powder, 50–300 μm	2	2	2	2	1	9	17.1	16.8	1.75	14.12	4.73
2	PG-R5M5 powder, 200–250 μm	2	1	2	2	1	8	16.2	15.8	2.47	14.71	4.99
3	Mixture of ferroalloy powders, 50–300 μm	2	1	2	2	1	8	13.6	12.6	7.35	16.18	6.08

the distribution histogram in Excel, there should be not less than 50 values in the data set. The histogram proper is formed with application of “Analysis Package” add-on.

As an example, this work gives an assessment of welding and technological properties of experimental flux-cored wires, which was conducted by the developed methodology. Comparison of the properties of flux-cored wires with different granulometric composition of the core material was performed, with granular metallic powder PG-R6M5 of two different fractions being applied as the core material in experimental wires (Table 2). Used as the standard was flux-cored wire with a core of a mixture of ferroalloy and other components, with their content calculated so as to ensure producing deposited metal of one chemical composition. The samples were produced by the method of submerged-arc surfacing under a layer of

AN-26P flux. The modes of surfacing and heat treatment of all the samples were the same, and the samples were surfaced in five layers. The idea of the research is described in more detail in [18].

Results of evaluation of welding and technological properties of experimental flux-cored wires are given in Table 2. The appearance of the surfaced samples is shown in Figure 1, and the histograms of distribution of instantaneous values of arc current and voltage are presented in Figure 2.

As one can see from the derived data, evaluation of the welding and technological properties of flux-cored wires, having similar characteristics, by just the qualitative parameters according to the procedure of [17], without taking into account the data on productivity and stability of the process, yields practically the same results (see the total number of points in Table 2).

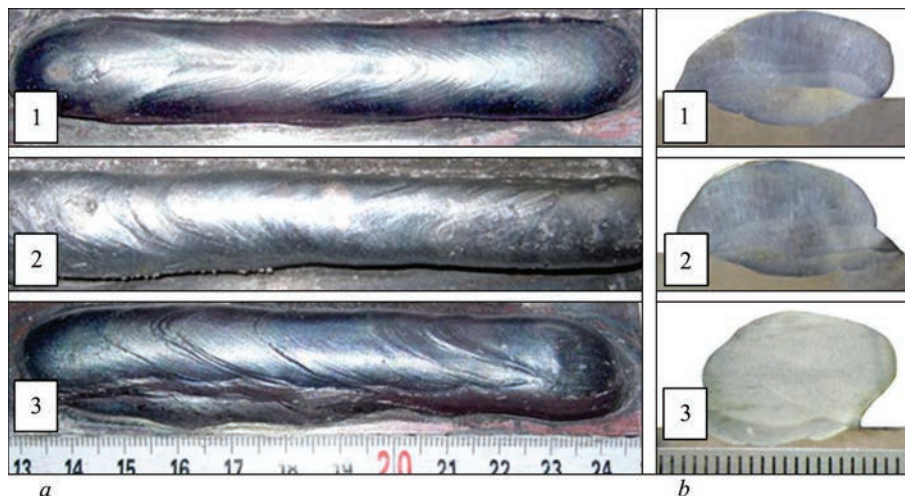


Figure 1. Appearance (a) and transverse macrosections (b) of samples surfaced in five-layers with wires Nos 1–3. Wire designations according to Table 2

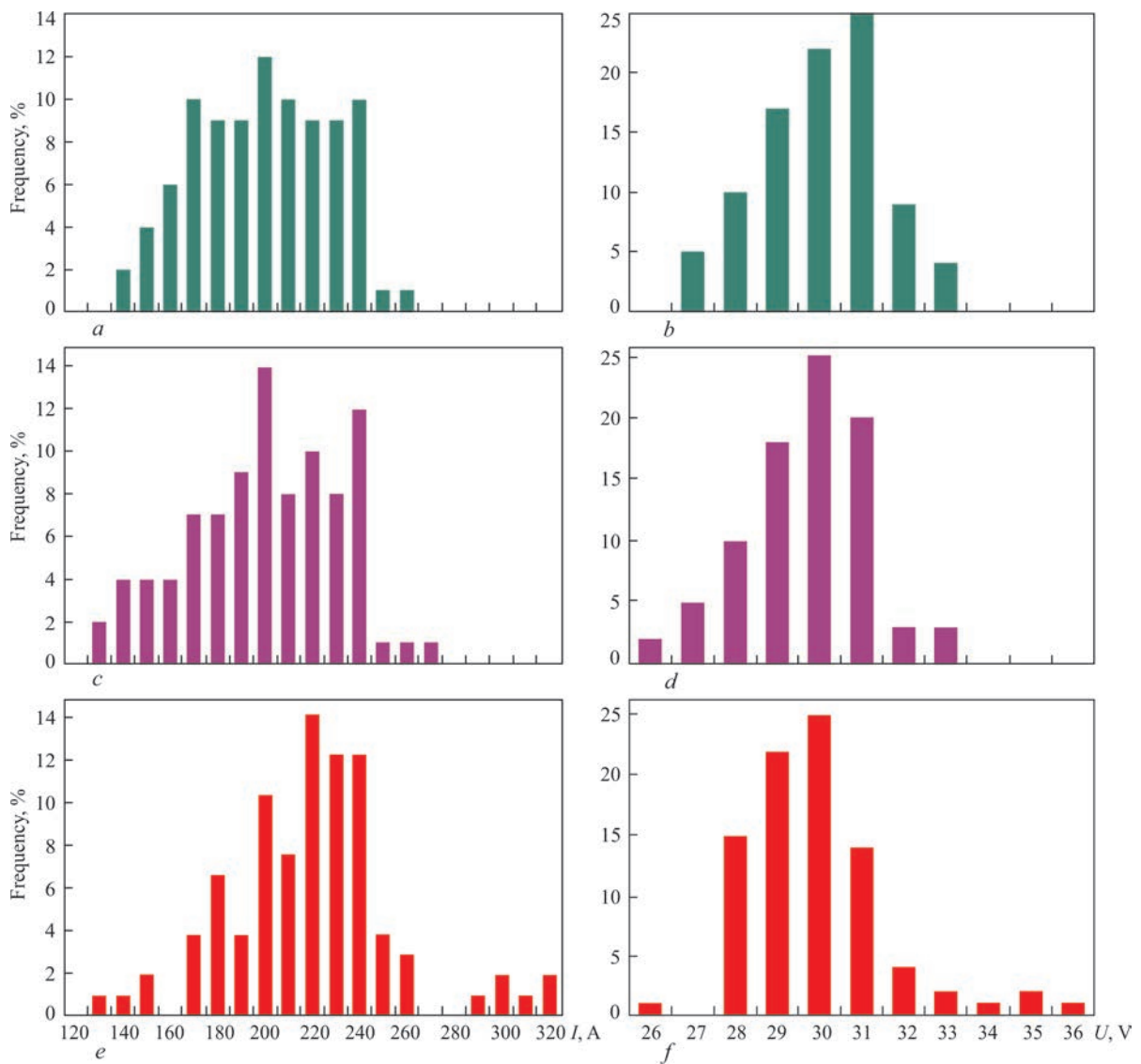


Figure 2. Histograms of distribution of current and voltage (*a, c, e*) and voltage (*b, d, f*) during surfacing with wires: No. 1 (*a, b*), No. 2 (*c, d*), No. 3 (*e, f*). Wire designations according to Table 2

Frequency, %

Performance of comprehensive analysis by the developed methodology, allowing for the melting and deposition rates, and the coefficient of losses, as well as the coefficients of variation by voltage and current and their distribution histograms, allowed determination of the increase in productivity and stability by 15–30 % during surfacing with experimental flux-cored wires (Nos 1, 2), compared to the wire-standard (No. 3).

CONCLUSIONS

1. A comprehensive methodology of comparative evaluation of the welding and technological properties of flux-cored wires for arc surfacing was developed, which is based on determination of the quality of deposited metal formation, parameters of process productivity and stability.

2. Application of the proposed methodology allows performing a comprehensive evaluation of the men-

tioned properties of flux-cored electrode wires, using quantitative characteristics, without application of complex and expensive software-hardware systems.

3. It was confirmed that the type and granulometric composition of metallic components of the core of flux-cored wires in electric arc surfacing influence the parameters and stability of the process, in particular, application of metallic granular powders of high chemical purity and homogeneity by physical properties, for instance of the type of R6M5, instead of the traditional ferroalloys, improves the welding and technological properties of flux-cored electrode wires.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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