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ANALYSIS OF THE COVERED ELECTRODE WELDING PROCESS STABILITY ON THE BASIS OF LINEAR REGRESSION EQUATION

ANALIZA STABILNOŚCI PROCESU SPAWANIA ELEKTRODĄ OTULONĄ NA PODSTAWIE RÓWNAŃ REGRESJI LINIOWEJ

The article presents the process of production of coated electrodes and their welding properties. The factors concerning the welding properties and the currently applied method of assessing are given. The methodology of the testing based on the measuring and recording of instantaneous values of welding current and welding arc voltage is discussed. Algorithm for creation of reference data base of the expert system is shown, aiding the assessment of covered electrodes welding properties. Statistical factors of instantaneous values of welding current and welding arc voltage waveforms used for determining of welding process stability are presented. The results of coated electrodes welding properties are compared. The article presents the results of linear regression as well as the impact of the independent variables on the welding process performance. Finally the conclusions drawn from the research are given.

Keywords: welding process stability, manual metal arc welding, digital welding current-voltage signals, wedling covered electrodes

Omówiono proces produkcji elektrod otulonych w kontekście ich właściwości spawalniczych. Przedstawiono wskaźniki właściwości spawalniczych oraz stosowaną dotychczas metodykę oceny. Omówiono metodyką badań polegającą na pomiarze i rejestracji wartości chwilowych natężenia prądu spawania i napięcia łuku spawalniczego. Przedstawiono algorytm tworzenia systemu bazy danych referencyjnych systemu eksperckiego, służącego do oceny właściwości spawalniczych elektrod otulonych. Omówiono stabilność układu źródło prądu – łuk spawalniczy. Przedstawiono wskaźniki statystyczne przebiegu wartości chwilowych natężenia prądu spawania i napięcia łuku spawalniczego służące do opisu stabilności procesu spawania

Zestawiono wyniki badań właściwości spawalniczych elektrod otulonych. Przedstawiono wyniki regresji liniowej oraz wpływ poszczególnych zmiennych niezależnych na wynik procesu spawania. Zaprezentowano wnioski z wykonanych badań.

1. Introduction

Covered electrode production is a complex process where many requirements should be met simultaneously. The functional properties of these electrodes, i.e. chemical composition and mechanical properties of the deposited metal and the whole range of the factors referred to as weldability are the reference points in this case [1, 2]. Inspection and verification of mechanical and chemical properties of deposited metal is conducted basing on the approved and standardised methods, i.e. static tensile test (PN-EN 10002), impact test (PN-EN 10045) or testing of chemical composition using method of emission spectrometry (PN-EN 26847). The quantitative methods that make it possible to assess unambiguously the welding properties of covered electrodes have not been found so far. One of the most important components of the covered electrodes weldability assessment is the stability of the welding process [3]. It is well known fact that only the stable process makes it possible to obtain a weld of a correct geometry, with practically not changing width and height of a weld face and penetration depth, what in the result increases the probability of obtaining the joint of the required mechanical properties [4-6].

The traditional method to assess and verify electrodes welding properties is the assessment made by a classifying welder, who performs it on the basis of the process observation during numerous welding trials. It is natural that the assessment made by a classifying welder is of a subjective character, however it is the only method used in practice so far. The classifying welder gains the experience and intuition in the evaluation over the course of the years and uses it during the assessment process. [3].

The range of testing during welding trials includes following components:

– the ability to stable the welding arc burning,
– the manner of the liquid metal transfer into the weld pool,
– behaviour of a liquid slag during welding,
– steady melting of the electrode (core and covering),
– spatter size.

The main goal of the experimental research is the at-

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tempt to create the expert system aiding the assessment of the covered electrodes welding properties on the basis of various tools of welding voltage and current real signals analysis. The research into the description of the welding process using voltage-current characteristics as the source of the valuable information has been conducted for many years [4, 7, 8]. The signals converted into a digital form can be easily stored in the computer memory and analysed using a number of tools for the descriptive analysis of signals. Analysis of the voltage-current signals has not yet been applied in the assessment of a welding process. This is partly due to the imperfection of the present monitoring systems and lacking of the unambiguous assessment criteria. Therefore those systems cannot be compared to the knowledge and experience of a welder and his ability to associating and assessing the welding conditions.

The basis of the expert system is the experience and knowledge of a specialist, this time a classifying welder, which becomes the knowledge base of the expert system being built. The first stage of the process of the system creation consists in the creating the reference base, i.e. repeated comparison of analysis factors with expert evaluation (Fig. 1)

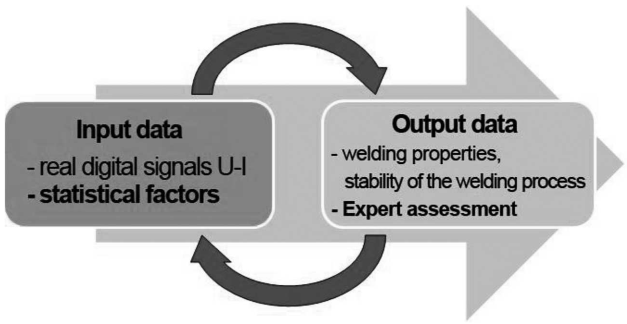

Fig. 1. Algorithm for creation of reference data base of the expert system aiding the assessment of covered electrodes welding properties

The simplest tool that can be used for forecasting welding properties of the electrodes is the method of linear regression. This article presents two equations describing welding properties of rutile electrode of E380R11 type determined using the linear regression and applying selected statistical factors.

Linear regression is the popular statistical tool used for forecasting of the expected value of the output variable y for known values of one or more input variables x. The expected variable y is called the *dependent variable* while input values x are *independent variables*. In the case of linear regression the liner function provides the model of dependencies between dependent and independent variables.

For one independent variable x the issue consists in the determination of the straight line $y = ax + b$ in the best possible way fitted to the set of n experimental points $\{(x_1,y_1),(x_2,y_2),\ldots,(x_n,y_n)\}$. The equation of multiple linear regression, where the dependent variable y values are the function of the independent variable x, is as follows:

$$y = b + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \tag{1}$$

where: y – dependent variable value to be determined
x_i – independent variable (input data)
a_i – regression coefficients
b – constant (the point of the intersection of a line with y axis)

The goal is to determine the regression coefficients $\boldsymbol{a}$ of the statistical model. The most often used method is the ordinary least squares approach and its modifications.

2. Stability of the power source – welding arc relation

From the theoretical point of view the stability is the ability of the system to return to the state of equilibrium when it becomes unbalanced due to various internal or external disturbances. Welding arc is a part of a electric circuit where current flow is forced by the welding power source [9]. It is known that welding arc is characterised by high dynamics and variability which result from the specificity of the electric discharges occurring between electrode and welded metal. During welding the arc is influenced by various disturbances resulting from a number of processes of physical and chemical nature, i.e. gaseous and metal vapour ionisation processes, liquid metal and slag transfer as well as weld pool refining metallurgical reactions [8]. Thus the direct relation of the power source – welding arc can be observed, that combines the welding power source of the specified static characteristic $U_d(I)$ with the electrode of the specified properties determined by the type of the coating and represented by the arc static characteristic $U_ł(I)$. The point of the intersection of both curves determines the optimum working point of the set "welding power source – welding arc" (Fig. 2). Oscillations of the parameters U-I around this point are directly connected with the welding power source dynamic characteristic and above mentioned disturbances in the arc operation. The measure of process stability is the speed of response of the system (power source) to the appearing disturbances.

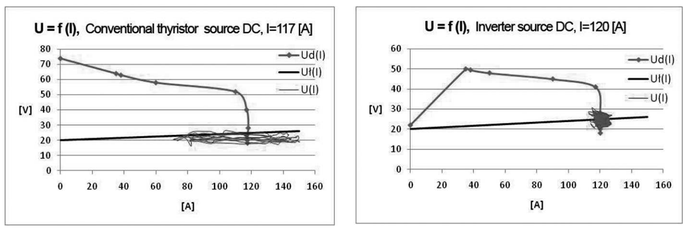

Fig. 2. The example of static real characteristics of the welding power source **Ud(I)** Conventional arc characteristic **Uł**=20+0,04I, real arc operation **U(I)**, Welding power source: conventional thyristor rectifier and inverter equipment. Electrode: E 380 R 11, ø3,2×350 mm

3. Processing and analysis of signals

In practice the signals processing and analysis are used in all fields of science and technology. The signal processing is the whole of the actions leading to depicting the observed signal in the form suitable for its further analysis, including standardisation and matching signals values, converting signal analogue values into digital ones, filtration and averaging of signals values in real time or transformation of the signal from one value space to the another (e.g. Fourier or Wavelet Transform, etc.) [11, 12]. The signals analysis should be understood as a searching for and determining of signals characteristics that makes it possible to identify information on the character and variability of the physical process being described by the signal. In practice the majority of analogue signals are converted into the digital form and all analysis operations are conducted on this type of signals. Digital signals differ from the analogue ones in that their values are described in discrete-time domain as a sequence of instantaneous values of the physical quantity being examined. In order to differentiate constant and discrete signals in time, various notations (forms of recording) are being used [11], namely:

– notation **x(t)** used traditionally in the recording of constant analogue signals in time,

– notation **x(n)** is applied for the recording of discrete time digital signals.

Fig. 3 shows the example of continuous (Fig. 3a) and discrete (Fig. 3b) signals.

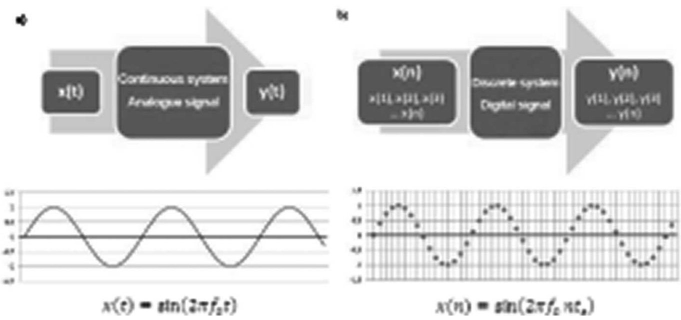

Fig. 3. a. Analogue signal, continuous in time x(t) f_o – frequency [Hz], t – time [s]; b. Digital signal, discrete in time x(n) f_o – frequency [Hz], n – sequence of natural numbers, t_s – sampling period [ms]

Voltage-current signals stored in the computer memory are the basis for further analysis using various statistic tools or methods applied in the digital analysis of the signals. The subject of this part of experimental research is the application of the method of linear regression to determine the relation between expert assessment – performed by the classifying welder, represented by the dependent variables *y*, and the parameters describing a welding process (determined on the basis of instantaneous values of voltage and current waveforms), represented by the independent variables *x*.

4. Description of a research station and a scope of research

The central component of the research station is the computer system for recording instantaneous values of welding voltage and current, which is based on multi-channel analogue-to-digital converters A/D of LC-011/16 type. Filtration system based on the noise galvanic separator is the integral part of the slotted line.

For testing one type of rutile electrode E380R11 of diameter 3,2×350 mm was selected. Besides the reference electrodes of the first grade characterised by the very good welding properties also defective electrodes of a clearly worse weldability were tested. During research two constant current welding power sources were used:

– three-phase conventional thyristor rectifier (maximum welding current 250 A),

– inverter source (maximum welding current 200 A).

For both group of electrodes a series of trials of welding and measuring of digital signals of voltage and current was performed. The recording of signals for three ranges of welding current: 90, 110 and 130A was carried out in real time. Padding welds were built up manually in flat position on metallically pure steel grade S235JR testpieces of dimensions of 150×80×5 mm. Welding speed was in the range of 23-25 cm/min, the angle between an electrode and material was 70°.

Welding trials and recording of voltage and current waveforms were performed at Welding Department of the Institute of Mechanic Technology, being the part of the Faculty of Mechanical Engineering and Computer Science of Częstochowa University of Technology.

Each time the samples of voltage and current signals were correlated with the classifying welder assessments using conventional criteria determined by the producer of the selected electrode type. In this process five-grade marking scale was applied where very good welding properties corresponded to the higher marks (5 maximum) while poor one to the lower marks (not less than 1).

Fig. 4 shows the example of current and voltage signals samples obtained during the experiment for both welding power sources.

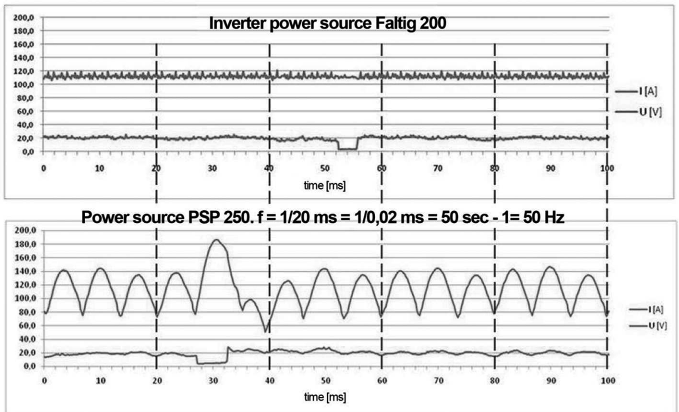

Fig. 4. Examples of real current signals (blue colour) and voltage (red colour). The current waveform for the inverter power source is clearly more consolidated (narrower range of variability) if compared to signals obtained for conventional source

In order to describe the welding process stability six statistical factors were selected as independent variable *x* [1, 2, 4, 13, 14]:

1. Mean value of welding voltage U_m
2. Standard deviation from medium value of welding voltage σ_U
3. Voltage coefficient of variation K_{vU}, which constitutes the ratio of standard deviation to mean value:

$$K_{vU} = \frac{\sigma}{Um} \cdot 100\% \quad (2)$$

Coefficient Kv makes it possible to illustrate the scatter of voltage values, as is considers the mean value of the measured voltage. Basing on research to date it was noticed that with the increase of coefficient K_{vU} the stability of arc burning deteriorates [2].

4. Short-circuit mean time Tz [ms]

TABLE 1

Statistical factors, independent variables x – electrode of E 380 R 11type

Welding power source	Conventional 3-phase thyristor						Inverter					
	Electrodes of good weldability I grade			Electrodes of a worse weldability, defective			Electrodes of good weldability I grade			Electrodes of a worse weldability, defective		
Current range	90A	110A	130A	90A	115A	130A	90A	110A	130A	90A	110A	130A
U_m [V]	20,1	19,6	21,0	26,1	29,1	32,9	19,2	20,5	20,4	26,9	28,6	33,8
σ_U [V]	4,7	4,6	4,9	6,1	5,5	3,7	4,8	5,1	5,5	6,2	6,1	4,0
K_{vU} [%]	23,2	23,3	23,4	23,3	18,8	11,4	25,1	25,1	26,8	22,9	21,3	11,9
Tz [ms]	4,0	3,1	2,3	2,0	1,6	1,1	4,5	3,8	3,2	2,2	2,2	1,5
Tj [ms]	72	51	49	41	64	195	68	60	44	45	59	229
Zw [s^{-1}]	14	20	20	24	16	5	15	17	23	22	17	4

5. Mean time of arc burning between short-circuits Tj [ms]
6. Average number of short-circuits during 1 second of welding Zw [s-1].

5. Research results

The Table 1 shows the values of six statistical factors selected during research, which create a base of independent variables x of six-fold regression equation.

The data prepared in such a way were set up in two Tables, separately for each welding power source. Independent variables (statistical factors) were denoted with $x_1, x_2, \ldots, x_6$ symbols, whereas output dependent data, being the assessment marks of classifying welder were denoted with symbol y.

TABLE 2

Independent data $x_1, x_2, \ldots, x_6$ and dependent data y. Conventional 3-phase thiristor welding power DC

Marking	x_1	x_2	x_3	x_4	x_5	x_6	Y
Statistical factors	U_m	σ_U	K_{vU}	Zw	Tz [ms]	Tj [ms]	Mark
90A (good)	20,11	4,67	0,23	13,85	4,01	72,22	5
90A (defective)	26,09	6,08	0,23	24,36	2,01	41,05	1
110A (good)	19,56	4,56	0,23	19,74	3,10	50,65	5
110A (defective)	29,06	5,48	0,19	15,64	1,57	63,93	1
130A (good)	20,95	4,90	0,23	20,26	2,35	49,37	5
130A (defective)	32,92	3,75	0,11	5,13	1,09	195,00	1

Linear regression equation (6) in this case is a six-component equation, what results from the application of six independent variables $x_1, x_2, \ldots, x_6$

$$y = b + a_1 U_m + a_2 \sigma_U + a_3 K_{vU} + a_4 Zw + a_5 Tz + a_6 Tj \quad (3)$$

In order to determine the regression coefficients of statistical model $a_1, a_2, \ldots, a_6$ for each dependent variable $x_1, x_2, \ldots, x_6$ respectively, the MS Excel program was used applying the table function *REGLINP.*

Linear regression equation describing the expected value of dependent variable y, for both tested welding power sources are as follows:

TABLE 3

Independent data $x_1, x_2, \ldots, x_6$ and dependent data y. Inverter DC welding power source

Marking	x_1	x_2	x_3	x_4	x_5	x_6	Y
Statistical factors	U_m	σ_U	K_{vU}	Zw	Tz [ms]	Tj [ms]	Mark
90A (good)	26,93	6,18	0,23	22,05	2,21	45,35	2
90A (defective)	19,18	4,81	0,25	14,62	4,49	68,42	5
110A (good)	28,59	6,10	0,21	16,92	2,21	59,09	2
110A (defective)	20,46	5,13	0,25	16,67	3,82	60,00	5
130A (good)	33,81	4,02	0,12	4,36	1,51	229,41	2
130A (defective)	20,44	5,47	0,27	22,82	3,16	43,82	5

– for conventional rectifier:

$$\boldsymbol{y = 26{,}41 - 0{,}84\, U_m + 0{,}76\, \sigma_U + 0\, K_{vU} - 0{,}24\, Zw - 1{,}39\, Tz + 0{,}01\, Tj} \quad (4)$$

– for inverter power source:

$$\boldsymbol{y = 32{,}91 - 0{,}79\, U_m + 0\, \sigma_U + 9{,}21\, K_{vU} - 0{,}29\, Zw - 2{,}38\, Tz - 0{,}002\, Tj} \quad (5)$$

Each equation includes six regression components, and in each equation there is one component of x with the coefficient a amounting to zero- factors K_{vU} and σ_U assume zero value in equation (4) and (5). Probably it is the result of the strong correlation between these two factors; K_{vU} is the ratio of standard deviation σ_U to voltage mean value U_r. Besides, it should be stressed that the value of factor K_{vU} is very high in equation (5), what shows the strong influence of this factor on the dependent variable y. On the other hand the lack of the influence of the factor K_{vU} on the variable y in equation (4) is surprising.

6. Conclusions

Separate factors $a_1, a_2, \ldots, a_6$ of the equation (4) and (5) describe the influence of the independent variables $x_1, x_2, \ldots, x_6$ on the value of the dependent variable y. In this particular case both functions illustrate the relation between the statistical factors $U_{śr}$, σ_U, K_{vU}, Zw, Tz, Tj (independent variables x) used in the analysis and the expected value of the assessment of welding properties (dependent variable y).

1. Voltage mean value $U_{śr}$. The coefficient a in both equation occurs with negative sign, what means that higher values of voltage corresponds to lower value of y, predicted assessment of welding properties of electrodes. In the other words the higher $U_{śr}$ the worse welding properties of electrodes.
2. Standard deviation σ_U occurs only for the conventional power source. The coefficient with positive sign (+0,76), what means, that higher values of the voltage standard deviation is accompanied by higher factors of the welding properties assessment.
3. Voltage coefficient of variation K_{vU} (only for inverter power source) shows very strong positive influence on the predicted value of the assessment y; small increase of K_{vU} value in equation (2) means very high increase of the assessment of welding properties. It can be observed that coefficient K_{vU} paradoxically shows reverse relation if compared with the stability assessment criterion used for the method 135 [1, 2]. In this case lower K_{vU} corresponds to electrodes of the worse welding stability.
4. Average number of short-circuit Zw (during 1 second). This factor has relatively small impact and reveals the negative influence of the number of short-circuits on the result of the assessment; the smaller number of short-circuits the better expected value of welding properties assessment y.
5. Short-circuit mean time Tz. The coefficients a for this independent variable occur with negative sign and are very high in both equations, what indicates strong impact of this parameter on the assessment result. The decidedly shorter short-circuit times which are accompanied by decidedly better welding properties are preferred.
6. Mean time of arc burning Tj. In both equations the influence of this factor is practically negligible.

The searching for the relations between statistical factors describing a welding process and expert assessment is very complex issue, nevertheless the results obtained have revealed the potential prospects to use linear regression for the estimation of coefficient value of electrode welding properties assessment.

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