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ISSN 0543-5846
METABK 55(2) 217-220 (2016)
UDC – UDK 621.791.052:669.182:620.17=111

THE OPTIMIZATION OF WELDING REGIME PARAMETERS AT SHIELDED METAL ARC WELDING (SMAW) BY MATHEMATICAL MODELING

Received – Primljeno: 2015-04-07
Accepted – Prihvaćeno: 2015-10-10
Preliminary Note – Prethodno priopćenje

The realized researches followed the determining of mathematical models that allow the optimization of the welding process in order to obtain welded joints with certain values of the mechanical characteristics. Thus, there were established mathematical models of dependence of mechanical characteristics of welded joints (R_m, R_{p02}, Z, A, K_{CV} 20 °C) of each parameter of welding regime (I_w, U_w), and also, mathematical models that offer cumulative dependence of mechanical characteristics of both parameters of welding regime.The researches have been carried out using steel E 36-4 as base material and as filler material basic electrodes, type E7018 and the applied welding procedure was the process: shielded metal arc welding (SMAW).

Key words: SMAW, steel, welding regime parameters, mechanical characteristics, optimization

INTRODUCTION

Welding opposed to other technology processes of manufacturing is significantly influenced by a relatively large number of process variables. These process variables are: base material (composition, thickness, internal defects, etc.); the filler material (electrodes type); base material surface condition (presence of dust, grease and oil); changing operator; the variation of the distance between two pieces that will be welded; variation of welding speed [1, 2].

The variables that can influence the welding process may be divided into two groups, namely: variables which can be controlled (welding current, welding voltage, welding speed, cleanliness of the surface of the base material, the length of the electric arc, the temperature of pre-heating); variables that cannot be controlled (size and temperature of the heat affected zone, mechanical tensions from welded joints, leakage of molten material) [3, 4]. Therefore, the optimization on experimental way of any welding process is often a very expensive activity with a high consumption of time.

In this way it is very important to control the welding regime parameters (welding current, welding voltage) so as to obtain the corresponding values for the mechanical characteristics of the welded joint. By processing the experimental data obtained in a process of experimentation there can be obtained a series of mathematical models that can be an important theoretical basis for establishing the optimum parameters of welding regime so as to obtain the desired mechanical properties for a welded joint. In these circumstances it is imperative to study the effects of parameters of welding regime on mechanical properties of welded joints and especially those made by the process of shielded metal arc welding (SMAW) [5, 6].

As bonding process this can be made in direct or alternative current, the power source which presents a descenders characteristic. The constant maintenance of arc's power is ensured by the control of the arc length by the welder operator [7, 8]. Manual welding is characterized by a high degree of versatility, both in terms of base materials, welding positions and material thicknesses that can be welded. The method is applied to steels welding, cast iron and non-ferrous materials. SMAW has a high degree of versatility and it can be used for difficult welding positions, and with the use of a wide variety of electrodes. The field of application of the process and the characteristics of the arc are connected to the electrode diameter, the welding current, arc voltage and the welding speed [9, 10].

MATERIALS AND METHODS

The researches aimed to establish the optimum welding parameters so as to obtain the best mechanical properties for welded joints made of steel E 36-4 by SMAW welding process. The use of this steel is indicated in the fabrication of resistance elements (beams, columns, sections, rails, brackets, etc.). In the experimental research it was taken into account the achieving of welded joints of tables with thickness of 10 / mm. It was also envisaged that the welded joints were made on a perpendicular direction to the laminating lines of the sheets.

Production technology of welded joints from steel E 36-4 recommended that until a thickness of 10 / mm not to preheat base material due to welding linear energy

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realize a sufficient preheating operation. To achieve desired results in the research, there were established initially for steel E 36-4 mechanical characteristics which are shown in Table 1.

Table 1 **Mechanical characteristics of steel E 36-4**

R_m / N / mm²	R_{p02}/ N / mm²	Z / %	A / %	K_{CV} 20 °C / J	K_{CV} 0 °C / J
559	197	22	33	61	64

Obtaining welded joints was performed considering the welding process SMAW using as the filler material a type E7018 with a diameter of Ø 3,25 / mm, and the filler material mechanical characteristics are shown in Table 2.

Table 2 **Mechanical characteristics of filler material**

R_m / N / mm²	R_{p02}/ N / mm²	A / %	K_{CV} 20 °C / J	K_{CV} 0°C / J
726	470	31	85	44

Shielded metal arc welding where the electric arc is primed between the electrode and the part to be welded is one of the commonly used methods. The electric arc melts the tip of the electrode and the base material forming the molten bath which is protected from the atmosphere action by the liquid slag layer and the gas generated during the melting of the coating on the electrode. The choice of welding regime parameters for SMAW envisages the realization of the best possible welding regimes to achieve experimental samples. So there have been chosen three groups of welding current (I_w) and three supply voltages for electric arc (U_w), that there is the possibility of finding the best solutions to weld. The groups of welding currents were established in range I_w = 210 – 250 / A, divided as follows:

a$_1$. I_w =210 – 225 / A;
a$_2$. I_w = 225 – 235 / A;
a$_3$. I_w = 235 – 250 / A.

The groups of welding voltage were established in range U_w = 24 – 35 / V, divided into:

b$_1$. U_w = 24 – 26 / V;
b$_2$. U_w = 27 – 31 / V;
b$_3$. U_w = 32 – 35 / V.

RESULTS AND DISCUSSIONS

The development of the process of experimental research was performed by realization 30 samples namely 3 samples for each of the 10 types of joints. For each type of joint were chosen different parameters of welding regime and thus in Table 3 the chosen parameters are denoted with 1. After the realization of the specimens, these were subjected to mechanical testing and the obtained values of mechanical characteristics are shown in Table 3, and this table shows the average values of the mechanical characteristics obtained for each welded joint.

Obtaining the average values of the mechanical characteristics was performed by execution of 5 samples for each welded joint. The results were processed using STATISTICA program, and this process was performed for each mechanical characteristic a multiple regression analysis, Table 4 and also, at the same time there were established the mathematical models that allow the establishing of the mechanical characteristics depending on the parameters of welding regime, Table 5. Through this mathematical modeling there can be optimized the parameters of welding regime depending on the mechanical characteristics.

At SMAW the evolution of mechanical characteristics of welded joints according to the parameters of welding regime, highlights the following:

– R_m has an increasing trend with the increasing of welding current (I_w), but very slow to values of 230 / A, and after this value increase is insignificant;
– R_m has an increase of the value given by the increase of welding voltage (U_w), but quite slowly evolving to a particular value of U_w of 29 / V, and after this value of U_w the increase of R_m is much faster;
– I_w and U_w influence R_m in ascending direction and the tension is influenced in a higher proportion, values of over 28 / V. Also, current intensity influence R_m, but in a much smaller proportion and only for values up to 230 / A, after which, while I_w increases, R_m is slightly increased;
– from multiple regression analysis given by the influence of I_w and U_w on R_m it can be noted the fact that

Table 3 **The mechanical characteristics of each type of welded joints for SMAW process**

No. of joint	No. of sample	Welding current I_w / A			Welding Voltage U_w / V			Mechanical characteristics				
		202,5	215	227	26	23,5	21,5	R_m / N / mm²	R_{p02}/ N / mm²	Z / %	A / %	K_{CV} 20 °C / J
I	$\bar{X}_I$	1	0	0	1	0	0	519	386	23,3	23,3	39,6
II	$\bar{X}_{II}$	0	1	0	1	0	0	517,6	380	23,6	24	43,0
III	$\bar{X}_{III}$	0	0	1	1	0	0	515	390	25,3	25,3	39
IV	$\bar{X}_{IV}$	1	0	0	0	1	0	521	386	26,3	27,3	42,6
V	$\bar{X}_V$	0	1	0	0	1	0	525	388,6	26,6	27	44,6
VI	$\bar{X}_{VI}$	0	0	1	0	1	0	522	390	26,3	25,6	41,3
VII	$\bar{X}_{VII}$	1	0	0	0	0	1	524	390	27	28,3	44,3
VIII	$\bar{X}_{VIII}$	0	1	0	0	0	1	517	392	28,6	28,6	46,3
IX	$\bar{X}_{IX}$	0	0	1	0	0	1	523	392	27,6	28,3	44,3
X	$\bar{X}_X$	0	1	0	0	1	0	527	389	26,25	26,50	44,25

Table 4 **Multiple regression analysis for the mechanical characteristics of welded joints obtained by the SMAW process**

Multiple Regresion Results $R_m = R_m(U_w, I_w)$
Dependent variable: R_m Multiple R : 0,978382563 F = 17,98036
R^2 : 0,96749539 df = 2,7
No. of cases: 10 Adjusted R^2 : 0,86753199 p = 0,007147
Standard error estimate: 0,988933896
Intercept: 512,73869509 Std. Error: 13,386092 t(7) = 19,759 p < 0,000754
I_w beta = 0,567 U_w beta = 0,951
Multiple Regresion Results $R_{p02} = R_{p02} (U_w, I_w)$
Dependent variable: R_{p02} Multiple R : 0,79318419 F = 5,937553
R^2 : 0,62914117 df = 2,7
No. of cases: 10 Adjusted R^2 : 0,52318150 p = 0,031062
Standard error estimate: 2,479728084
Intercept: 325,77073941 Std. Error: 24,36533 t(7) = 13,370 p < 0,0000
I_w beta = 0,405 U_w beta = 0,682
Multiple Regresion Results $Z = Z (U_w, I_w)$
Dependent variable: Z Multiple R : 0,93137980 F = 22,90878
R^2 : 0,86746834 df = 2,7
No. of cases: 10 Adjusted R^2 : 0,82960215 p = 0,000847
Standard error estimate: 0,679546100
Intercept: 3,470997375 Std. Error: 6,677090 t(7) = 0,51984 p < 0,0000
I_w beta = 0,202 U_w beta = 0,909
Multiple Regresion Results $A = A (U_w, I_w)$
Dependent variable: A Multiple R : 0,93222617 F = 23,22687
R^2 : 0,86904562 df = 2,7
No. of cases: 10 Adjusted R^2 : 0,83163009 p = 0,000813
Standard error estimate: 0,754826986
Intercept: 10,375787402 Std. Error: 7,416785 t(7) = 1,3990 p < 0,2045
I_w beta = 0,016 U_w beta = 0,932
Multiple Regresion Results $Kcv = Kcv (U_w, I_w)$
Dependent variable: Kcv Multiple R : 0,79776707 F = 6,126818
R^2 : 0,63643230 df = 2,7
No. of cases: 10 Adjusted R^2 : 0,53255581 p = 0,028977
Standard error estimate: 1,594422224
Intercept: 38,952723097 Std. Error: 15,66649 t(7) = 2,4864 p < 0,0418
I_w beta = - 0,018 U_w beta = 0,776

Table 5 **Mathematical models of the mechanical characteristics depending on parameters of welding regime for SMAW process**

No.	Dependencies	Mathematical model
1	$R_m = R_m(I_w)$	$R_m = 223,857 + 3,87 \cdot I_w – 0,017 \cdot I_w^2$
2	$R_m = R_m(U_w)$	$R_m = 569,781 – 2,153 \cdot U_w + 0,049 \cdot U_w^2$
3	$R_m = R_m(U_w, I_w)$	$R_m = 112,937 + 4,116 \cdot I_w - 1,975 \cdot U_w – 0,019 \cdot I_w^2 - 0,013 \cdot I_w \cdot U_w + 0,017 \cdot U_w^2$
4	$R_{p02} = R_{p02}(I_w)$	$R_{p02} = 1,059^3 – 5,956 \cdot I_w + 0,013 \cdot I_w^2$
5	$R_{p02} = R_{p02}(U_w)$	$R_{p02} = 363,146 + 0,992 \cdot U_w – 0,004 \cdot U_w^2$
6	$R_{p02} = R_{p02}(U_w, I_w)$	$R_{p02} = 919,219 – 5.659 \cdot I_w + 6,559 \cdot U_w + 0,014 \cdot I_w^2 - 0,02 \cdot I_w \cdot U_w – 0,021 \cdot U_w^2$
7	$Z = Z(I_w)$	$Z = - 198,144 + 1,892 \cdot I_w – 0,004 \cdot I_w^2$
8	$Z = Z(U_w)$	$Z = - 11,239 + 2,135 \cdot U_w – 0,029 \cdot U_w^2$
9	$Z = Z(U_w, I_w)$	$Z = - 262,813 + 1,848 \cdot I_w + 4,377 \cdot U_w – 0,003 \cdot I_w^2 – 0,01 \cdot I_w \cdot U_w – 0,027 \cdot U_w^2$
10	$A = A(I_w)$	$A = - 78,341 + 0,899 \cdot I_w – 0,002 \cdot I_w^2$
11	$A = A(U_w)$	$A = - 4,394 + 1,613 \cdot U_w – 0,019 \cdot U_w^2$
12	$A = A(U_w, I_w)$	$A = - 168,105 + 1,047 \cdot I_w + 4,503 \cdot U_w - 0,001 \cdot I_w^2 – 0,013 \cdot I_w \cdot U_w – 0,017 \cdot U_w^2$
13	$K_{cv} = K_{cv}(I_w)$	$K_{cv} = - 1,419^3 + 12,652 \cdot I_w – 0,027 \cdot I_w^2$
14	$K_{cv} = K_{cv}(U_w)$	$K_{cv} = 4,121 + 2,14 \cdot U_w – 0,027 \cdot U_w^2$
15	$K_{cv} = K_{cv}(I_w, U_w)$	$K_{cv} = - 1,402^3 + 12,513 \cdot I_w – 0,664 \cdot U_w – 0,027 \cdot I_w^2 + 0,005 \cdot I_w \cdot U_w + 0,001 \cdot U_w^2$

both U_w and I_w as well as have a positive influence on the mechanical strength in the sense that their value increases with the increasing of the value of R_m. However, U_w ,s influence is much higher compared to the influence of I_w (I_w beta = 0,951; U_w beta = 0,567);

– R_{p02} is influenced by I_w and remains approximately constant up to I_w values of 230 / A, and over these values of I_w there was observed an increasing trend of R_{p02};
– R_{p02} is influenced by two parameters of welding regime, but it was noted the fact that the influence in ascending direction is given by I_w for values above 230 / A. For I_w values between 220 - 230 / A, increases of R_{p02} are small and are almost not influenced by the value of I_w;
– from multiple regression analysis of R_{p02} dependence of parameters of welding regime is observed the fact that I_w has a smaller influence on R_{p02} (I_w beta = 0,405; U_w beta = 0,682);
– with the increase of I_w, there was an increase in the value of *Z* and this increase is more pronounced to the values of I_w = 230 / A, and over these values *Z* remains approximately constant;
– an ascending pronounced evolution of *Z* is given by the increase of U_w up to a value of 29 / V, and over these values of U_w, *Z*'s growth is quite low;
– *Z* present highest values for U_w = 23 / V and I_w up to 230 / A, with the observation that lower values of *Z* are obtained for U_w = 24-28 / V and I_w that takes values up to 230 / A At current values over 230 / A, although U_w has small values, it was noticed an increase of *Z*;
– from multiple regression analysis it was observed the influence of I_w and U_w on Z, and especially the proportion of influence (I_w beta = 0,202, U_w beta = 0,909) and thus it was established that the influence of U_w on Z is approximately 4 times higher compared to the influence of I_w;
– *A* increases to values of $I_{w=}$ 230 / A, after which there was noticed a slight decrease with the maximum decrease value of *A* for a value of I_w = 232 / *A*;
– *A*'s increase with the increase of U_w is pronounced to a value of 29 / V after which growth slows;
– large increases of *A* are obtained where U_w has values above 28 / V and I_w has values in the range 220 - 235 / A. For values of U_w of 24 - 28 / V and values of I_w of 220 - 240 / A values of *A* are relatively small. Over these parameter values of welding regime *A* is maximum for U_w = 33 / V and I_w = 230 / A;
– from the multiple regression analysis of the dependence of *A* on the welding regime parameters was observed that U_w has great influence on the value of *A*, while Iw has a much smaller influence (I_w beta = 0,016; U_w beta = 0,932);
– K_{cv} increases with the increase of U_w, but shows a rather slow growth and for higher values of U_w over 30 / V increases of K_{cv} are smaller;
– upward trend of K_{cv} is slow when I_w values are increased up to 230 / A, and over this value of Iw there was observed that K_{cv} decreases at a high rate;
– K_{cv} increases with increasing of I_w to maximum values of about 230 / A, and for values of Iw larger than this value was a sharp decline of K_{cv}. U_w show a positive effect on the whole range of variation, the maximum value of K_{cv} was obtained for values of I_w = 228 - 232 / A and U_w = 31 - 33 / V;
– to observe the influence of each parameter of welding regime on K_{cv} there was performed a multiple regression analysis in which it was observed that greater influence has U_w (U_w beta = 0,776 positively) K_{cv} ,s growth, and I_w influence is smaller (I_w beta = - 0,18 negatively), thus, with increasing values of I_w, K_{cv} presents a decreasing trend.

CONCLUSIONS

The results obtained in experimental research, and the processing of these shows:

- each measured mechanical characteristic is influenced differently by welding regime parameters and take different values for each value of welding regime parameters;
- multiple regression analysis gives us a synthetic image of how the welding regime parameters influence each mechanical characteristic;
- mathematical modelling is very efficient because it allows setting the values of parameters of welding regime so as to obtain a certain value for the mechanical characteristics.

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Note: The responsible translator for the English language is Dicu Maria-Camelia, Targu Jiu, Romania.