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OPTIMIZATION BY CALCULATION METHOD OF PULSED-ARC WELDING MODES USING HIGH ALLOY WELDING MATERIAL

A.V. Zavdoveev[1], **V.D. Poznyakov**[1], **O.A. Gaivoronskyi**[1], **A.M. Denysenko**[1] and **T. Baudin**[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]Université Paris-Saclay, CNRS, Institut de Chimie Moléculaire et des ma Tériaux d»Orsay
91405 Orsay, France. E-mail: thierry.baudin@u-psud.fr

The use of modern pulsed-arc welding technologies allows a significant improvement of the quality of welded joints. However, a large number of possible welding modes hinder the development and implementation of pulse technologies in modern production. This is associated with the fact that in pulsed-arc welding at least four independently variable parameters exist, which in totality requires a large number of experiments to determine their impact. To optimize the number of experiments in this study, the experimental calculation Taguchi algorithm for the process of pulsating arc welding using a high alloy welding material was implemented. The quantitative contribution of each variable welding parameter in the formation of the penetration depth is shown. The optimal welding modes were proposed, providing a set penetration depth. 15 Ref., 6 Tables, 4 Figures.

Keywords: pulsating arc welding, penetration depth, Taguchi algorithm, high alloy welding material

Pulsed-arc welding (PAW) is qualitatively different from traditional welding in shielding gases [1–4]. This is predetermined by expanded capabilities of PAW in affecting the processes of melting and transfer of the electrode metal, formation of the structure in the weld and HAZ metal of welded joint, regulating the weld shape, penetration depth, etc. Today, this method of welding is increasingly used in world practice in the manufacture of critical welded structures from high-strength steels [4–7].

At present, the leading companies developed many inverter welding current sources based on pulse technologies for MIG/MAG welding. Thus, the Swedish Company Esab developed the power source Aristo 500, the American Company Hobart — Ultra-Arc 350, the German Company EWM — Phoenix 501 pulse. Due to a wide range of tasks that can be solved in PAW, they are in demand in the domestic production of critical metal structures. However, it should be noted that these sources have built-in programs with a wide range of modes, from which it is difficult to choose the optimal one for a specified variant of welding.

In PAW, there are four variable mode parameters: base current (I_b), pulse current (*IP*), frequency (*f*), and duty cycle (*C*). Therefore, while choosing a mode, it is necessary to conduct a large number of experiments. Also, a well-known experimental calculation Taguchi method exists [8], which allows evaluating the influence of each of the parameters of a mode on welded joint formation.

The aim of the work was to make the selection of PAW modes using the Taguchi method, which provide a set penetration depth of the V-shaped groove without a gap of a butt joint of high-strength alloy steel with a reverse weld formation with the use of a high-alloy welding material.

Table 1. Selected parameters for PAW

Parameter	Note	Level					
		Value			Coding		
		Minimum	Mean	Maximum	Minimum	Mean	Maximum
Pulse current, A	A	160	200	240	1	2	3
Pause current, A	B	80	120	140	1	2	3
Frequency, Hz	C	0.5	1	5	1	2	3
Duty cycle, %	D	40	60	80	1	2	3

A.V. Zavdoveev — https://orcid.org/0000-0003-2811-0765, V.D. Poznyakov — https://orcid.org/0000-0001-8581-3526,
O.A. Gaivoronskyi — https://orcid.org/0000-0002-5922-5541, Baudin T. — https://orcid.org/0000-0002-6765-360X

Table 2. Performance of tests on the base of designing plan

Number	Pulse current, A		Pause current, A		Frequency, Hz		Duty cycle, %	
	Value	Code	Value	Code	Value	Code	Value	Code
1	160	1	80	1	0.5	1	40	1
2	160	1	120	2	1	2	60	2
3	160	1	140	3	5	3	80	3
4	200	2	80	1	1	2	80	3
5	200	2	120	2	5	3	40	1
6	200	2	140	3	0.5	1	60	2
7	240	3	80	1	5	3	60	2
8	240	3	120	2	0.5	1	80	3
9	240	3	140	3	1	2	40	1

Experimental procedure. When performing the investigations, the parameters of PAW by pulsating arc were selected, which are given in Table 1.

In the mentioned experiment there are four independently controlled process parameters and three experimental levels. In full, for four factors and three levels it would be necessary to conduct a $3^4 = 81$ experiment. The method proposed by Taguchi uses orthogonal arrays (OAs) for determination of the minimum number of experiments in real time to evaluate all designing factors. In such an experimental scheme, each factor is evaluated individually and one does not affect the other. The conditions that emerged in this study, i.e. four parameters together with their three levels, are suitable for the selection of the L9 matrix as an experimental project. Table 2 presents nine experimental tests in real time, which were compiled as specified in the scheme L9 (3^4) according to the Taguchi method [8, 9]. In this case, the experiments should be carried out in random order to bypass noise sources.

Calculation of signal-to-noise ratio. When conducting experiments, different process parameters are used, which give different values of «response». As a «response», penetration depth (PD) was chosen. In the course of experimental tests, it was necessary to evaluate the influence of each selected factor with the help of the received «responses», which may not be unique and have both desirable and undesirable characteristics. According to the Taguchi method, the signal/noise ratio (*S*/*N*) is a deviation of the qualitative characteristic from the desired value. During calculation of the S/N ratio, one should choose among the three available operating values — a higher, a lower and a nominal one (HB, LB and NB).

The calculation of the *S*/*N* ratio was performed according to the equation (1). The generalized calculated *S*/*N* ratios for all experiments are presented in Table 3.

$$\frac{S}{N} = -10\log\left(\frac{\sum_1^n \frac{1}{Y^2}}{n}\right). \quad (1)$$

The next step in the analysis consists in dividing the influence of each individual parameter on all three considered levels and ranking them in the order of their influence on the response parameter. This is possible because the selected experimental scheme corresponds to the orthogonal L9 matrix [10].

The average efficiency of the factor is calculated by dividing the sum of the test results including the factor by a number of the tests performed at the same level (equation (2)):

$$\text{for example, } \langle S/N \rangle_{A1} = (S/N_1 + S/N_2 + S/N_3)/3. \quad (2)$$

Contribution of individual factors to the penetration depth. Rated control of the final answer requires knowledge of the degree of contribution of individual process parameters, and they can be evaluated using a statistical method, namely ANOVA [11]. In the ANOVA methodology, *SS*, *SS*′, *D*, *V* and *P* are typical symbols of the parameters, used in the abovementioned analysis to represent the factors, sum and adjusted

Table 3. Results of measuring penetration depth and signal-to-noise ratio

Number	Parameters				Response		*Q*/*V*, kJ/mm
	Pulse current, A	Pause current, A	Frequency, Hz	Duty cycle, %	PD	*S*/*N*	
1	160	80	0.5	40	0.88	–1.128	0.42
2	160	120	1	60	2.159	6.673	0.55
3	160	140	5	80	2.47	7.851	0.61
4	200	80	1	80	3.37	10.55	0.68
5	200	120	5	40	3.31	10.4	0.62
6	200	140	0.5	60	2.091	6.374	0.72
7	240	80	5	60	2.926	9.322	0.67
8	240	120	0.5	80	3.597	11.12	0.93
9	240	140	1	40	3.349	10.5	0.75

sum of squares, degree of freedom, dispersion and a percentage contribution of each factor, respectively [12, 13]. A brief explanation of the abovementioned factors is presented below.

The total sum of SS_T squares can be calculated from the S/N ratio from the equation (3), which uses the terms «total number of experiments ($m = 9$)» and «i-th current signal-to-noise ratio ηi:

$$SS_T = \sum_{i=1}^{9} S/N_i^2 - \frac{1}{9}\left(\sum_{i=1}^{9} S/N_i\right)^2. \quad (3)$$

The sum of squares of factors, denoted as SS_p is calculated by the equation (4), which has the following conditions: factor «p», number of its level as «j», repetition of each level for the tested factor p, as «t» (= 3), summation of the signal-to-noise (S/N) ratio, that connects this coefficient p and its level j as $S/Npj = (S/N_1 + S/N_2 + S/N_3)$ for the level $A_j = 1$, $(S/N_2 + S/N_3 + S/N_4)$ for the level $A_j = 2$, $(S/N_7 + S/N_8 + S/N_9)$ for the level $A_j = 3$

$$SS_P = \sum_{j=1}^{3} \frac{\left(\sum S/Npj\right)^2}{3} - \frac{1}{9}\left(\sum_{i=1}^{9} S/N_i\right)^2. \quad (4)$$

The degree of freedom (DOF) is one of the elements that should be taken into account when calculating ANOVA [11]. D_p and V_p are the notations used to represent the degree of freedom and the dispersion of the factor p. V_p is determined as a percentage with the use of SS_p from D_p in accordance with the equation (5).

$$V_p(\%) = \frac{SS_p}{D_p} \cdot 100. \quad (5)$$

The summation of DOF, accompanied near the tests and the mean value, is called the total DOF. The degree of freedom for the mean value is always equal to 1. Therefore, the total degree of freedom for this experimental study is 8, which is equal to the number of tests (9 tests) –1, and the degree of freedom for the parameters is 2, which is obtained by subtracting 1 from the number of parameter levels (3 levels).

The difference between SS_p (sum of squares of factors) and the product of the dispersion of errors and DOF of each test factor is called the adjusted sum of squares and is denoted as SS_p which is calculated by the equation (6).

$$SS'_P = SS_P - D_P V_e. \quad (6)$$

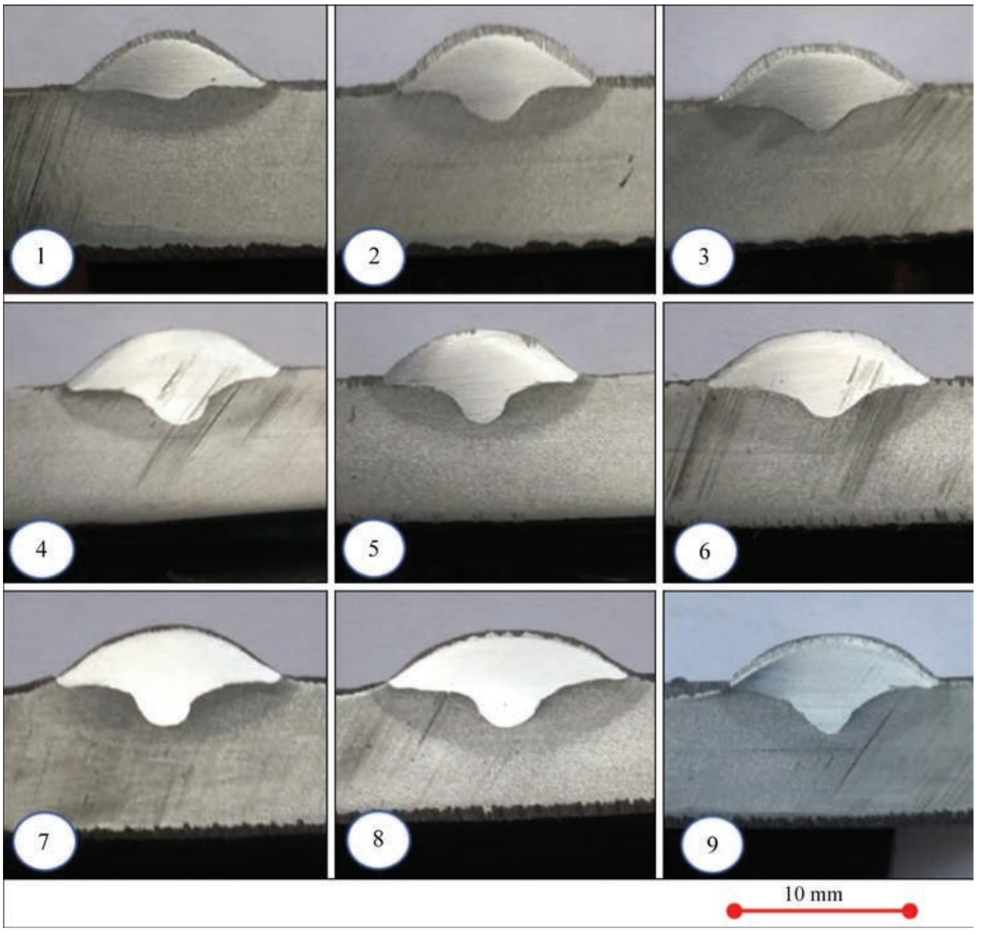

Figure 1. Photo of macrosections of experimental deposits

Table 4. Calculation of *S*/*N* values according to the algorithm of Taguchi

Parameter	Note	Level 1	Level 2	Level 3	Δ = max–min	Rank
Pulse current, A	A	4.465	9.107	10.31	5.85	1
Pause current, A	B	6.249	9.395	8.241	3.15	4
Frequency, Hz	C	5.454	9.24	9.189	3.79	2
Duty cycle, %	D	6.588	7.456	9.84	3.25	3

The percentage ratio of the tested factors between their corrected sum and the total sum of squares is called their percentage contribution and is denoted as P_p. The equation (7) is used to determine P_p:

$$P_p(\%) = \frac{SS'_P}{SS_T}\cdot 100. \quad (7)$$

Results and discussion. Macrosections of the deposits produced in accordance with the program (Table 2) are shown in Figure 1, where the number corresponds to the surfacing mode. The results of the calculation of the penetration depth for the mentioned specimens are given in Table 3.

Using the Taguchi algorithm, taking into account the corresponding values of the signal-to-noise ratio, the mean values for each level and welding parameter are calculated, which are given in Table 4.

As is seen from the calculations, pulse current for penetration depth parameter is ranked by the number «1», which indicates that it has the greatest influence on penetration depth than on pause current, frequency and duty cycle.

The ANOVA results provide information on the quantitative contribution of each parameter.

Compliance test for checking repeatability. After selecting the optimal level of designing process parameters, this is a mandatory step to determine and check the improvement of quality characteristics with the use of the optimal level of designing parameters. According to [11–15], the predicted signal-to-noise ratio for the optimal level of the design process parameters can be calculated as

$$\hat{\eta} = \eta_m + \sum_{i=1}^{n}(\bar{\eta}_i - \eta_m). \quad (8)$$

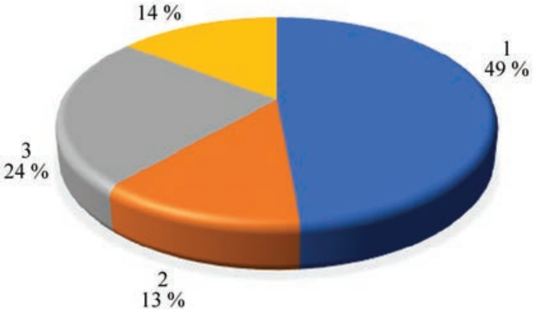

Figure 2. Results of calculations by ANOVA method: 1 — pulse current; 2 — pause current; 3 —frequency; 4 — duty cycle

In the abovementioned equation, η_m η_i and n represent the mean *S*/*N* ratio (Table 4) and the total number of important projects of experimental parameters affecting the quality. The predicted *S*/*N* ratio can be found using the optimal parameters of the pulsating arc welding process (Tables 5, 6).

The results of checking the predicted welding modes in order to obtain the maximum and minimum penetration depth during pulsating arc welding are shown in Figure 3. As is seen, the experimental-calculation algorithm of Taguchi makes it possible to predict the response of the studied parameter, namely penetration depth with a high accuracy.

The results of the studies were used while selecting the optimal PAW mode for the root layer of the V-shaped joint of high-strength steel, the groove of which was made without a gap and had a 4 mm blunting (Figure 4). At the same time, it was possible to obtain the proper quality of the welded joint, namely to provide penetration of the groove root with the reverse weld formation already in the course of the first experiment.

It should be noted that the Taguchi method can also be used when selecting PAW modes for multilayer joints in order to obtain the optimal HAZ dimensions. This is a very important factor that significantly affects the technological and operational properties

Table 5. Results of evaluating the predicted number and confirming the results for the optimal state of the PA-GMAW process (PD is the maximum)

Parameters	A	B	C	D	S/N	
					Prediction	Experiment
Optimal coded value	3	2	2	3	14.9	12.04
Optimal value	240	120	1	80		
Deviation = 19 %.						

Table 6. Results of evaluating the predicted number and confirming the results for the optimal state of the PA-GMAW process (PD is the minimum)

Parameters	A	B	C	D	S/N	
					Prediction	Experiment
Optimal coded value	2	1	2	1	–1.13	–1.21
Optimal value	200	80	1	40		
Deviation = 7 %						

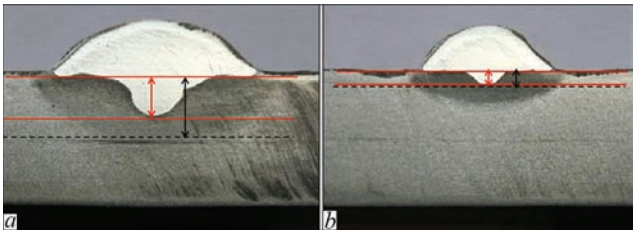

Figure 3. Macrosections of deposits produced according to the calculated modes, with maximum (*a*) and minimum (*b*) PD (dotted line shows calculated value of penetration and solid line shows experimental one)

of welded joints of critical metal structures made of high-strength alloy heat-hardened steels. The studies in this direction are performed and the results will be presented in future publications.

Conclusions

1. A study of the influence of pulsed-arc welding modes (welding current, pause current, frequency, duty cycle) on penetration depth using a high-alloy welding wire by means of the experimental calculation Taguchi method was carried out. The possibility of controlling the parameters of pulsating arc welding in order to obtain the required penetration depth in a wide range was shown.

2. It was found that pulse current has a predominant influence on penetration depth. The influence of frequency, duty cycle and pause current is the next in importance. The quantitative analysis revealed that the influence of these parameters is distributed as follows: pulse current — 49 %, pause current — 13 %, frequency — 24 %, duty cycle — 14 %.

3. The carried out studies allowed proposing the optimal modes of pulsed-arc welding, which provide the set values of penetration depth, namely the minimum and the maximum one. The verification experiment showed that within the limits of insignificant deviations the predicted values of penetration depth correlate with the experimental ones.

4. Experimental calculation Taguchi method is a powerful and promising tool that can be used while selecting the optimal modes and in the development of pulsed-arc welding technologies.

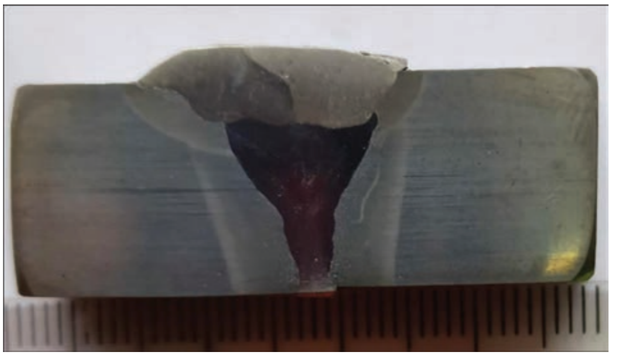

Figure 4. Butt joint of high-strength steel (V-shaped, without a gap, 4 mm blunting)

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