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EFFECTIVENESS OF APPLICATION OF PULSED MODE OF ARC BURNING IN WET UNDERWATER WELDING

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ABSTRACT

A comparative analysis of methods for implementing the pulsed nature of arc burning — pulsed-arc welding by changing the shape of the external volt-ampere characteristic of the power source and pulsed wire feeding and their parameters when welding with flux-cored wire with a non-stationary arc in an aqueous environment was carried out. The results obtained showed the greater efficiency of using pulsed welding wire feed: the coefficient of variation in voltage decreases by 1.5 times, and the frequency of short circuits — by 2.5 times; the depth of penetration and reinforcement of the weld changes by 63 and 55 %, respectively; the transition of alloying elements C, Si, Mn and Ni increases by 38, 30, 47 and 35 %, respectively; a study of the hydrogenation mechanism during wet underwater welding showed that most of the hydrogen (60–70 %) enters the weld pool along with a drop of electrode metal, which is saturated with it from the atmosphere of the vapour-gas bubble. Pulse action shortens the lifetime of liquid metal at the droplet stage, which leads to a decrease in the hydrogen content in the weld metal by an average of 27 %.

KEYWORDS: wet underwater welding, flux-cored wire, pulsed mode, effectiveness

INTRODUCTION

Pulsed methods of controlling the welding process allow for improving the welded joint quality, performing adjustable heat input into the welded joint zone, regulating the electrode metal melting mode and formation of the structure of weld metal and heat-affected zone (HAZ), and reducing the burnout and spattering losses [1–5]. Pulsed-arc welding (PAW) is considered the best-known variant of adjusting the value of thermal energy input into the arc burning zone. In this case, the power source directly controls, according to a set program, the electric parameters of the welding arc, namely pause and pulse currents and their duration [6–10].

A power source with a flat volt-ampere characteristic (VAC) is usually used in flux-cored wire wet underwater welding. The range of welding current variation during welding can reach 150–200 A. The welding process proper is accompanied by periodical short-circuiting (Figure 1) [11–13]. Such a chaotic state partially depends on the specificity of the environment. In particular, in wet underwater welding, the process stability will be additionally influenced by the collapse of the vapour-gas bubble. Turbulent flows forming in this case,

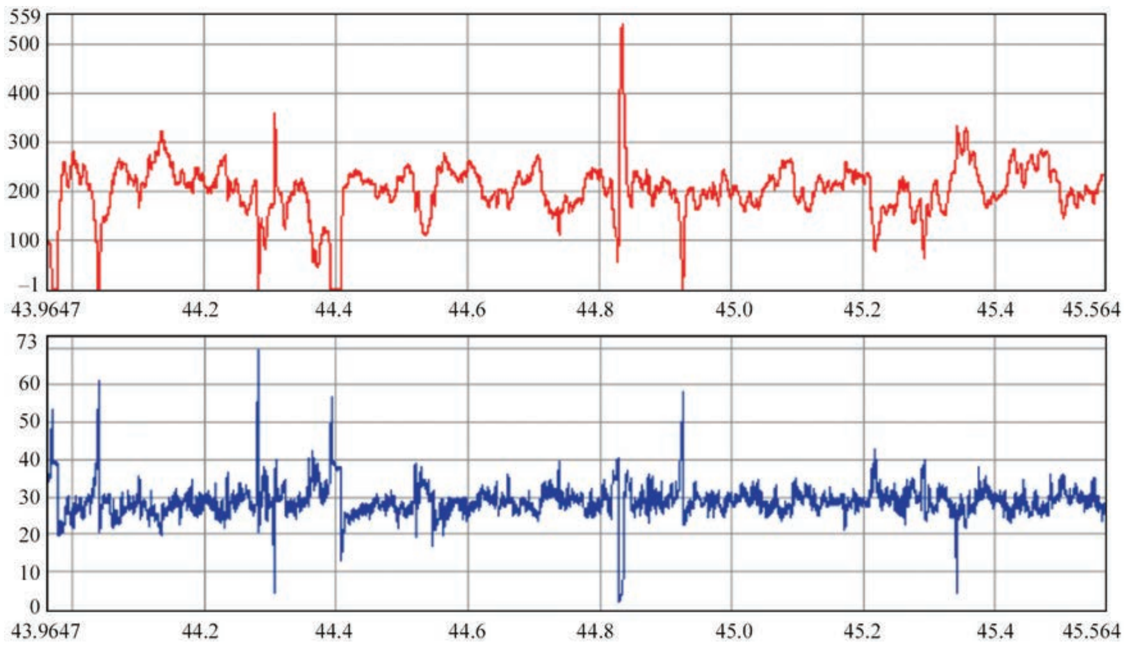

Figure 1. A typical oscillogram of the process of underwater welding with PPS-AN1 flux-cored wire

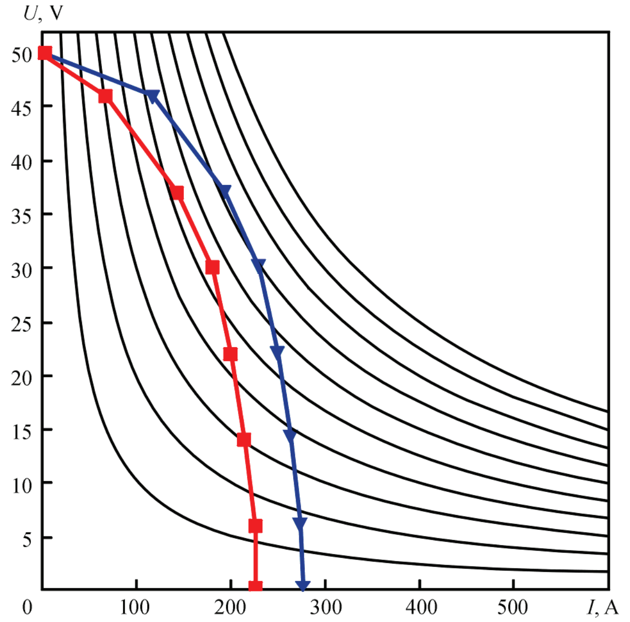

Figure 2. Example of VAC shape for pulsed welding

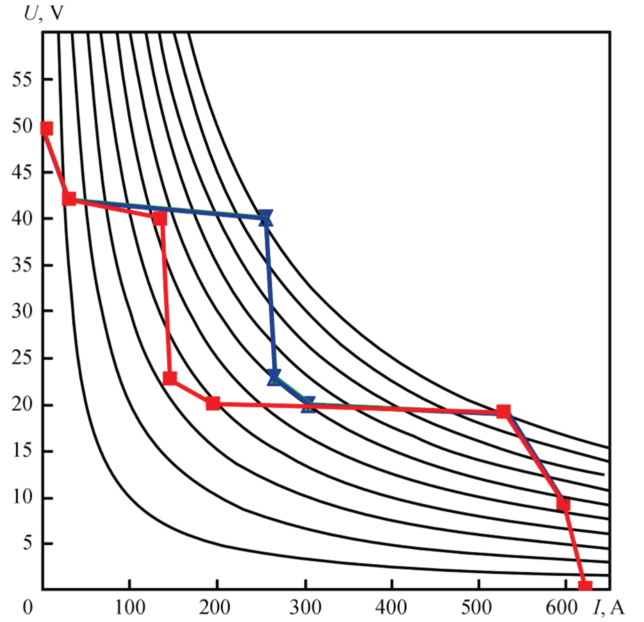

Figure 3. Example of VAC with shape correction

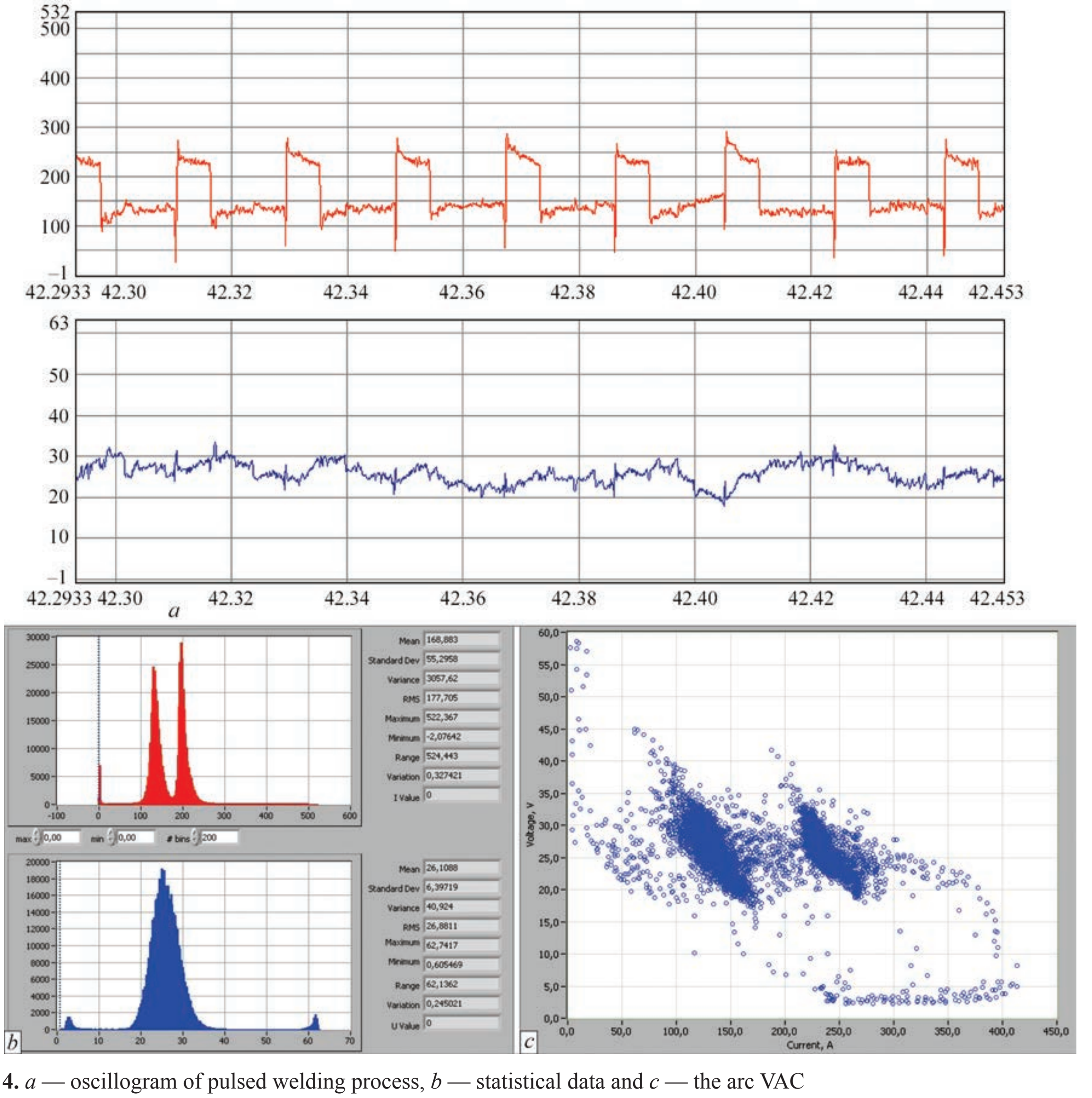

Figure 4. *a* — oscillogram of pulsed welding process, *b* — statistical data and *c* — the arc VAC

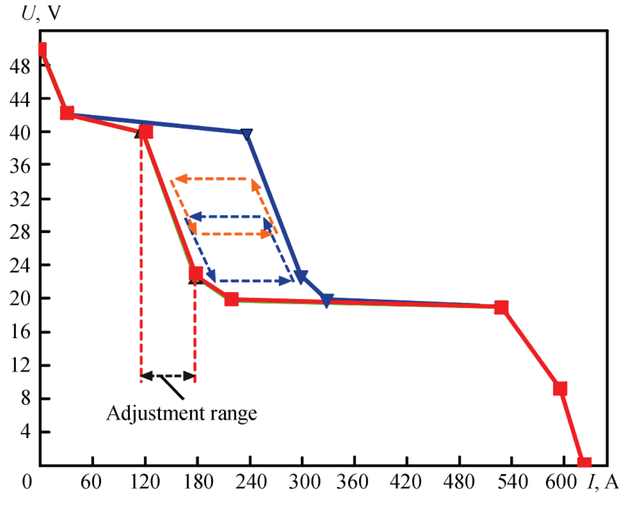

Figure 5. Variants of the trajectory, depending on wire feed rate and range of possible values

throw the bubble up. As a result, part of the drops will be lost to spatter. When penetrating into the weld pool, the other part of the drops, usually after gaining a certain weight, causes disturbance on the latter's surface. Considering the high cooling rate, these disturbances do not have enough time to subside, and after solidification, we observe an irregularity of the weld surface.

The research aimed to conduct a comparative analysis of the methods for implementing the pulsed nature of arc burning — pulsed arc welding (PAW) — by changing the shape of the external volt-ampere characteristic (VAC) and the pulse feed of the welding wire (PFW) and their parameters when performing the flux-cored wire welding process with a non-stationary arc in an aqueous environment.

METHODS

LET-500 power source was used to solve the welding problem, which allows relatively flexible adjustment of most process parameters, including the shape of external volt-ampere characteristics [14, 15]. Its pulsed mode of operation enables using two such VACs, each with its own operating time, as shown in Figure 2. When switching from one characteristic to another, the welding current changes to the respective value for the currently used characteristic.

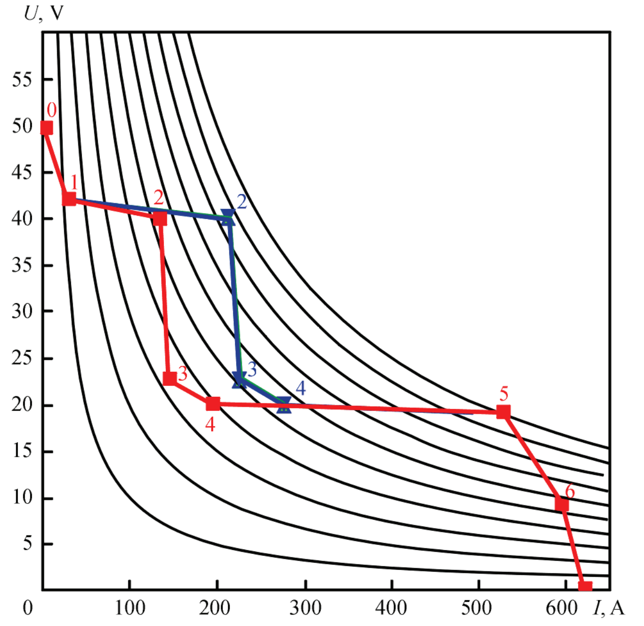

Figure 6. VAC sections for pulsed welding

Previous experiments showed that this combination of VAC shapes is unstable and can lead to freezing and interruption of the welding process. To avoid such a situation, it is necessary to correct the VAC shape, by adding arc power at the moment close to the short-circuit (Figure 3). A typical oscillogram of the process, statistical data and VAC of the arc are shown in Figure 4. One can see from the oscillogram how the pulse-to-pause transition is realized. The Figure also shows the graphs of current and voltage distribution.

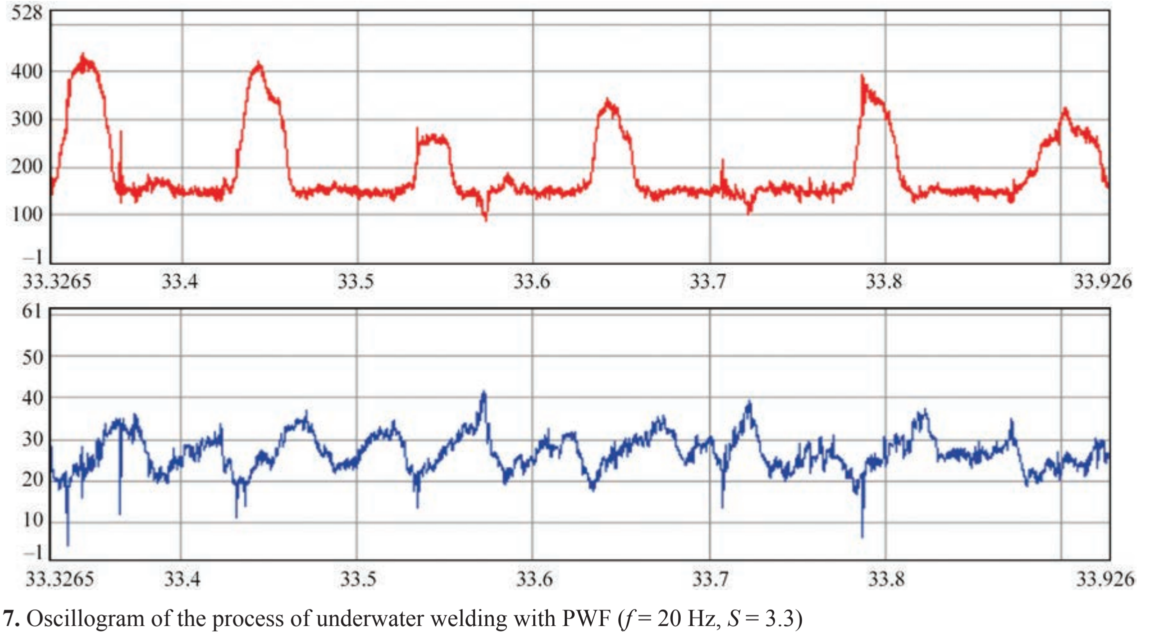

Figure 7. Oscillogram of the process of underwater welding with PWF ($f = 20$ Hz, $S = 3.3$)

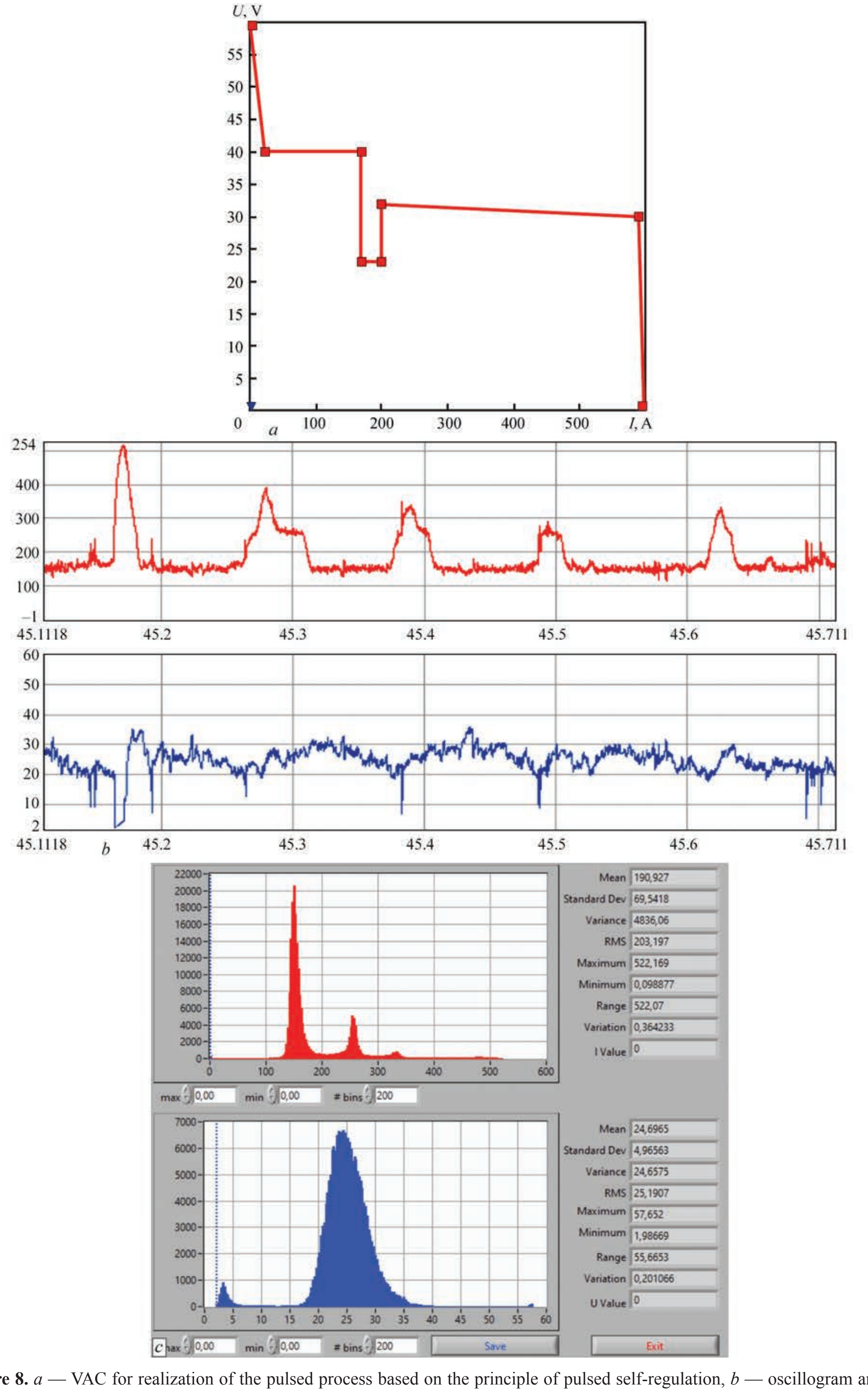

Figure 8. *a* — VAC for realization of the pulsed process based on the principle of pulsed self-regulation, *b* — oscillogram and *c* — histogram of the process of welding with this VAC

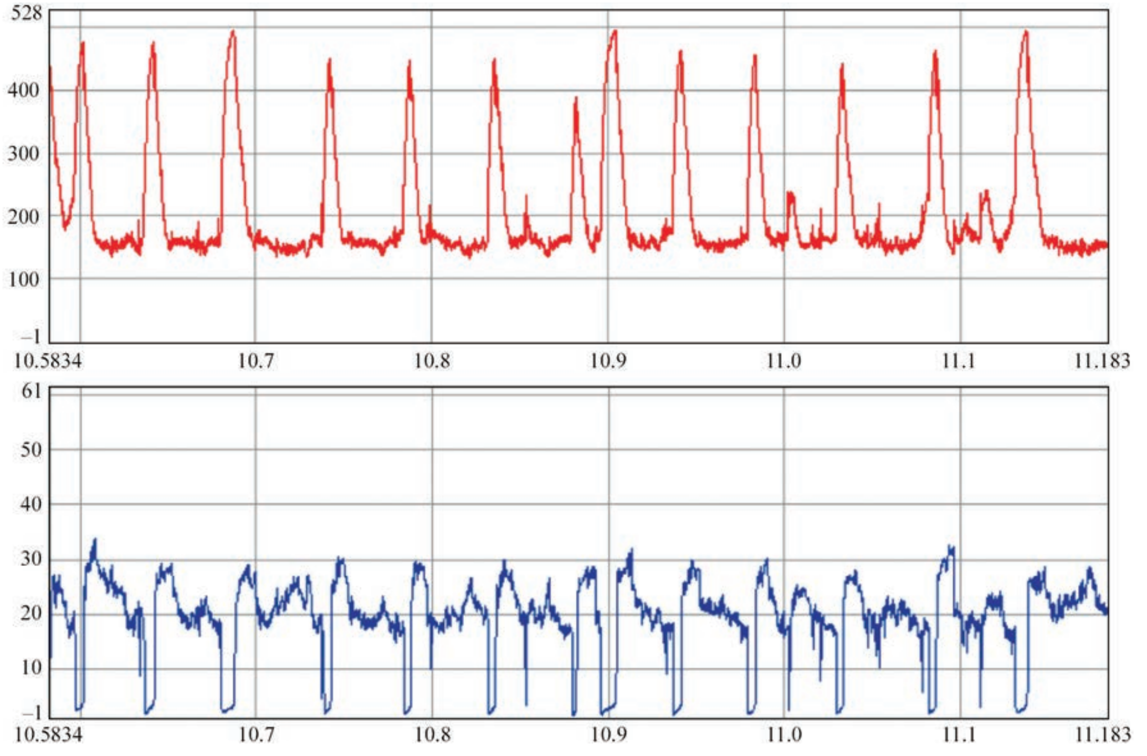

Figure 9. Oscillogram of the welding process with VAC based on the principle of pulsed self-regulation in combination with PWF (f = 20 Hz, S = 3.3)

Note that during welding, it is difficult for us to influence the arc directly. It can cause the formation of rolls and slag entrapment along the weld edges. To a greater extent, the voltage will depend on the distance from the molten electrode tip to the weld pool. At a constant feed rate, a current change promotes a change in the electrode melting rate. This leads to the electrode tip moving closer to or farther from the weld pool. Here, the working point of welding on the volt-ampere characteristic moves according to a trajectory shown in Figure 5. The resulting average voltage value is between the trajectory upper and lower boundaries. Given the above, we can influence the voltage in several ways. The first parameter that should be paid attention to is welding speed. A slight increase or decrease in the welding speed will shift the trajectory and, as a result, change the position of its boundaries. The second important factor is the slope and duration of the falling portion of the power source VAC. Adjustment sensitivity and its degree depend on it.

Pulse and pause current were determined by current in point 3 for the VAC blue and red line (Figure 6). Such selection is conditional, as more parameters should be taken into account for a more accurate determination. Despite that, the current in point 3 approximately coincides with peak values on current distribution graphs. To set a certain pulse or pause current, fixed region 2–3–4 was shifted along the horizontal.

Welding with pulsed welding wire feed (PWF) should be regarded as another variant with pulsed process of welding control [16–18]. This process is performed through adjustment of welding wire rate and duration of movement during the pulse and pause in the feed mechanism (Figure 7).

This process was realized by applying a drive based on a collectorless valve motor, which ensures both the pulsed and constant welding wire feed [19]. The range of feed frequency in the pulsed mode is from 1 up to 60 Hz, and the wire feed rate is up to 2280 m/h. Unlike PWF, where the power source is electronically controlled, and the process of switching from the pulse to pause runs instantly, a smooth change between these phases is observed in this process. This is due to the inertia of the system, which appropriately incorporates the engine, wire feed mechanism, and welding wire.

We should also mention welding with a broken VAC, which is based on the principle of pulsed self-regulation (Figure 8). In the current histogram (Figure 8, *b*), one can see an absence of arc breaks, unlike the regular process (Figure 1). The latter variant can be combined with the variant with PWF for more flexible control of the welding process (Figure 9).

The given examples and available equipment confirm that the specified welding and control modes ensure a pulsed process and also allow the following:

- establishing the value and duration of pause and pulse current for PWF.
- determining the rate and duration of the wire feed in the pause and pulse phase for welding with PWF. In this case, the pause current depends on the wire feed rate. Due to inertia, a smooth change of current and voltage parameters at the switching of pause and pulse phases is observed.

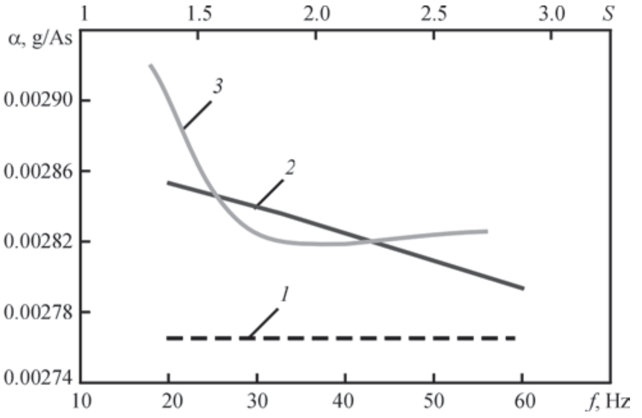

Figure 10. Dependence of deposition rate on the relative pulse duration (*S*) and frequency (*f*) of the process of welding with PWF: *1* — no pulse; *2* — *S* =3.3; *3* — *f* = 40 Hz

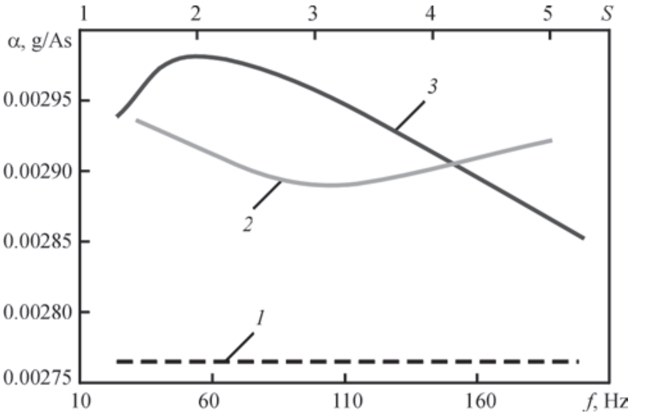

Figure 11. Dependence of deposition rate on relative pulse duration (*S*) and frequency (*f*) of the process for PWF: *1* — no pulse; *2* — *S* =2; *3* — *f* = 50 Hz

● pause current limiting by VAC falling portion for the welding variant with broken VAC. It provides a better-controlled process in combination with PWF. In this case, unlike the simple process with PWF, there is the possibility of a more accurate determination of the pause current. Unlike pulsed self-regulation, PWF enables more precise control of the process stability.

In order to assess the influence of pulsed actions on the efficiency of the process of flux-cored wire wet underwater welding, bead deposition on plates from 10 mm 09G2S steel was performed. During welding, the current and voltage signals were recorded for further processing. In order to increase the accuracy of the obtained results, the number of tests in one point was equal to 3. The derived data were used to plot the respective graphs of the dependencies.

RESULTS AND DISCUSSION

Results of measurements of the deposition rate are given in Figures 10 and 11. As one can see from the given data, with the pulsed nature of the arc burning, a slight increase in the amount of deposited metal is possible within 6–8 %.

To detect the influence of welding process parameters on weld geometry, the welding modes remained fixed: welding speed of 9 m/h with approximately the same average welding current of 185 A. Table 1 shows the degree of the influence of pulsed process parameters on weld dimensions for both the welding processes.

Obtained results demonstrate the possibility of adjustment of the geometrical parameters of the weld metal, using the pulsed process parameters in welding in an aqueous environment. Compared to PWF with the same current and voltage, applying pulsed wire feed allows a more significant impact on weld penetration depth and convexity in the frequency range from 20 to 60 Hz and relative pulse duration from 1.43 to 10 units. Compared to welding in the stationary mode, it is possible to control the penetration depth in the range from –18 up to +45 % and weld convexity in the range from –38 up to +17 %. The extent of influence on the weld width is small in both cases.

Table 1. Influence of pulsed process parameters on weld dimensions

Parameter	Welding with PWF			PAW		
	min, mm	max, mm	Influence, %	min, mm	max, mm	Influence, %
w	14	16.44	15.5	11.66	13.5	13.6
h	2.07	3.65	62.7	1.21	1.71	29.2
g	2.97	5.63	55.2	4,51	5.11	11.7

Table 2. Results of chemical composition analysis

No.	*f*, Hz	S	C, %	Si, %	Mn, %	Ni, %
1	–	–	0.08	0.02	0.17	1
2	40	1.43	0.08	0.018	0.11	0.9
3	40	3.33	0.1	0.021	0.18	1.35
4	40	10	0.11	0.02	0.25	1.26
5	20	3.33	0.06	0.018	0.2	0.8
6	60	3.33	0.11	0.026	0.21	1.3

Table 3. Diffusible hydrogen content in the deposited metal

No.	*f*, Hz	S	[H], $cm^3/100$ g
1	–	–	30.55
2	40	1.43	31.2
3	40	3.33	28.14
4	40	5	35.4
5	20	3.33	27.3
6	60	3.33	22.17

The main elements in the analysis of the influence of the pulsed mode of arc burning were carbon, silicon, manganese and nickel, present in the composition of flux-cored wire. As shown by the obtained data (Table 2), the use of PWF, compared to welding with constant wire feed, allows controlling the deposited metal chemical composition in a wide range: C — –25 to +38, Si — –10 to +30, Mn — –35 to +47, Ni — –20 to +35 %.

The presence of high hydrogen content in the weld metal is a critical factor that significantly impairs the quality of the welded joint. This issue is particularly urgent in underwater welding, where, under otherwise equal conditions, the quantity of hydrogen in the weld metal is 1.5–1.9 times greater than under normal conditions. This increase is due to the high partial pressure of hydrogen in the arc atmosphere and the higher weld pool crystallization rate, both of which are unique to underwater welding. Addressing this issue is crucial to improving the quality and reliability of underwater welds.

Pulsed welding processes influence the energy input, arc length, time of existence of molten metal pool, etc., which, in turn, determines weld metal saturation with hydrogen. Knowing the nature of this influence, it is possible to predict the probability of forming of the defects (pores, cold cracks, etc.), which impair the welded joint properties.

The chromatographic method was used to determine the diffusible hydrogen content $[H]_{dif}$ in the deposited metal. The deposition was performed on 10×15×25 mm samples, which were placed into gas analyzer chambers immediately after welding. The process with pulsed feed of flux-cored wire turned out to be more effective: total hydrogen content decreased by 37 % on average. Table 3 gives the results of $[H]_{dif}$ measurement for each sample.

Summary effects of welding with PWF are given in Table 4.

Table 4. Alloying element content in the weld metal

Parameter	Welding with PWF		
	min, %	max, %	Influence, %
C	0.06	0.11	45.5
Si	0.016	0.022	27.3
Mn	0.11	0.25	56
Ni	0.8	1.35	40.7
	min, $cm^3/100$ g	max, $cm^3/100$ g	
$[H]_{dif.}$	22.17	35.4	37.4

CONCLUSIONS

1. Comparative analysis of the methods of implementation of pulsed mode of arc burning, namely pulsed-arc welding (PAW) due to the change of external volt-ampere characteristic (VAC) and pulsed welding wire feed (PWF), and of their parameters during flux-cored wire non-stationary arc welding in an aqueous environment was performed. It was found that at PWF, it is possible to accurately determine the required value and duration of the pause and pulse current; welding with PWF allows the wire feed rate and duration to be established in the pause and pulse phase. In this case, the pause current depends on the wire feed rate. A smooth change of current and voltage parameters is observed due to inertia when switching between the pause and pulse phases. For the welding variant with a broken VAC, the VAC falling portion limits the pause current. This provides a better-controlled process in combination with PWF. In this case, unlike the simple process with PWF, it is possible to determine the pause current more accurately. And, unlike pulsed self-regulation, there is the possibility of more precise control of the process frequency due to PWF.

2. The pulsed process parameters influence on the weld metal dimensions and shape was assessed. The welding modes remained fixed: welding speed of 9 m/h, average welding current of 185 A. The rate of welding wire feed in the pulse (PWF) and pulse current (PAW) were the correction parameters to set the welding mode. Analysis of the measurement results of the weld geometrical dimensions showed that in welding with PWF at the same current and voltage, pulses allow much more significant influence on weld penetration depth and convexity — 63 and 55 %, respectively. The influence of PWF parameters on weld width is small. Compared to other devices, the influence on penetration depth is greater at the application of a pulsed power source, but it is not higher than 29 %. The influence on the width and convexity is 2.5 times smaller, equal to 13.5 and 11.7 %, respectively. Thus, welding with PFW widens the range of influence on weld dimensions at the change of process parameters.

3. It was established that the use of PWF, compared to welding with constant wire feed, allows for a significant degree of control over the deposited metal composition, with a range of up to 56 %. Modes with a frequency of 50 to 60 Hz and a relative pulse duration of 5 to 6 units correspond to a more significant transition of alloying elements.

4. The effectiveness of the pulsed process for weld metal degassing was thoroughly investigated. The study of the hydrogenation mechanism revealed that the majority of hydrogen (60–70 %) enters the weld pool with the electrode metal drop, which is saturated by it from the vapour-gas bubble atmosphere. Pulsed impact significantly reduces the time of existence of liquid metal at the drop stage, leading to a substantial reduction in the amount of hydrogen in the weld metal. The process with pulsed feed of flux-cored wire was found to be particularly effective, with the total hydrogen content decreasing by an average of 37 %. The influence of gas saturation for oxygen and nitrogen is minimal, not exceeding 5 %. This finding underscores the practical implications of the effectiveness of the pulsed process in reducing the amount of hydrogen in the weld metal.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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