https://doi.org/10.37434/tpwj2022.03.02

EFFECT OF PARAMETERS OF PULSED-ARC WELDING ON THE FORMATION OF WELD METAL AND MICROSTRUCTURE OF HEAT-AFFECTED ZONE OF 09G2S STEEL

S.Yu. Maksymov, D.M. Krazhanovskyi, Yu.A. Shepelyuk, S.V Osynska

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

One of the promising ways to solve the problem of increasing the service life of welded structures is the development of welding methods based on the use of pulsed control of energy parameters of the process. The pulsed mode of welding allows performing a regulated heat input in the welded butt joint zone, controlling the mode of melting the electrode metal, forming the structure of weld metal and heat-affected zone (HAZ). It was found that with an increase in the frequency of pulsed-arc welding, it is possible to reduce the width of the HAZ and the region of a coarse grain. Thus, in the case of welding low-alloy steels, due to the use of technology with a pulsed process, there is a prospect of reducing the width of the overheating region, which is important for the cases of repair of pipe wall thinning during remelting of defects in the operating pipeline using a mechanized method.

KEYWORDS: main pipelines, pulsed-arc welding, technological parameters, welded joint, geometric parameters, structure

INTRODUCTION

At present, oil and gas-oil equipment and main pipelines become objects of increased danger because of their technical condition. This circumstance causes the need in using effective methods of repair. With the help of traditional welding methods, it is difficult to solve all technological problems that are complicated: providing the possibility of regulating penetration depth in a wide range, welding over increased gaps and in different spatial positions, joining of metals and alloys dissimilar in their composition, reduction of sputtering of electrode metal, increase in the stability of arc ignition and its burning [1].

The main problem in welding of position butt joints of main pipelines is to provide the necessary quality of root, filling and facing layers and a high level of mechanical characteristics in a butt to be welded. It is known that up to 90 % of defects revealed during testing of the quality of welded joints, are associated with defects in the root layers of welds: undercuts, lacks of penetration, nonmetallic inclusions, pores [2]. The main cause for appearance of these defects, except for a poor preparation of a butt to be welded, is a violation of welding conditions (welding speed, arc voltage, current), as well as their inconsistency with the necessary values that provide producing high-quality welded joints. Traditionally, the used processes of manual welding can provide the necessary quality of welded joints only during a careful preparation of a butt to be welded and the use of high-quality materials.

The gained experience shows that pulsed methods of welding process control allow solving the following technological problems:

- controlled and directed transfer of electrode metal [3–5];
- possibility of welding in all spatial positions and simplification of welding techniques [6, 7];
- improvement of quality of welded joints due to the greater concentration of the power of the heating source and the better conditions of primary crystallization [5, 8, 9];
- reduction of losses on burn and sputtering [4, 10].

The analysis of literature showed that at a pulsed feeding the weld structure is fine-grained and disoriented, and the mechanical properties of welded joints are higher than in welding with short circuits of an arc gap [11–13]. The application of pulses allows a significant increase in the intensity and stability of arc discharge, the hydrodynamic processes in the welding pool and the conditions of its crystallization are changing. The pulsed increase in the pressure of the arc improves the formation of the weld, the weld bead becomes fine-rippled and refining of the microstructure associated with the collision impact of electrode metal droplets is observed [14–16].

The aim of the carried out investigations was to determine the impact of welding and frequency f of the process of pulsed-arc welding on geometric dimensions of the deposits and structural transformations in the HAZ.

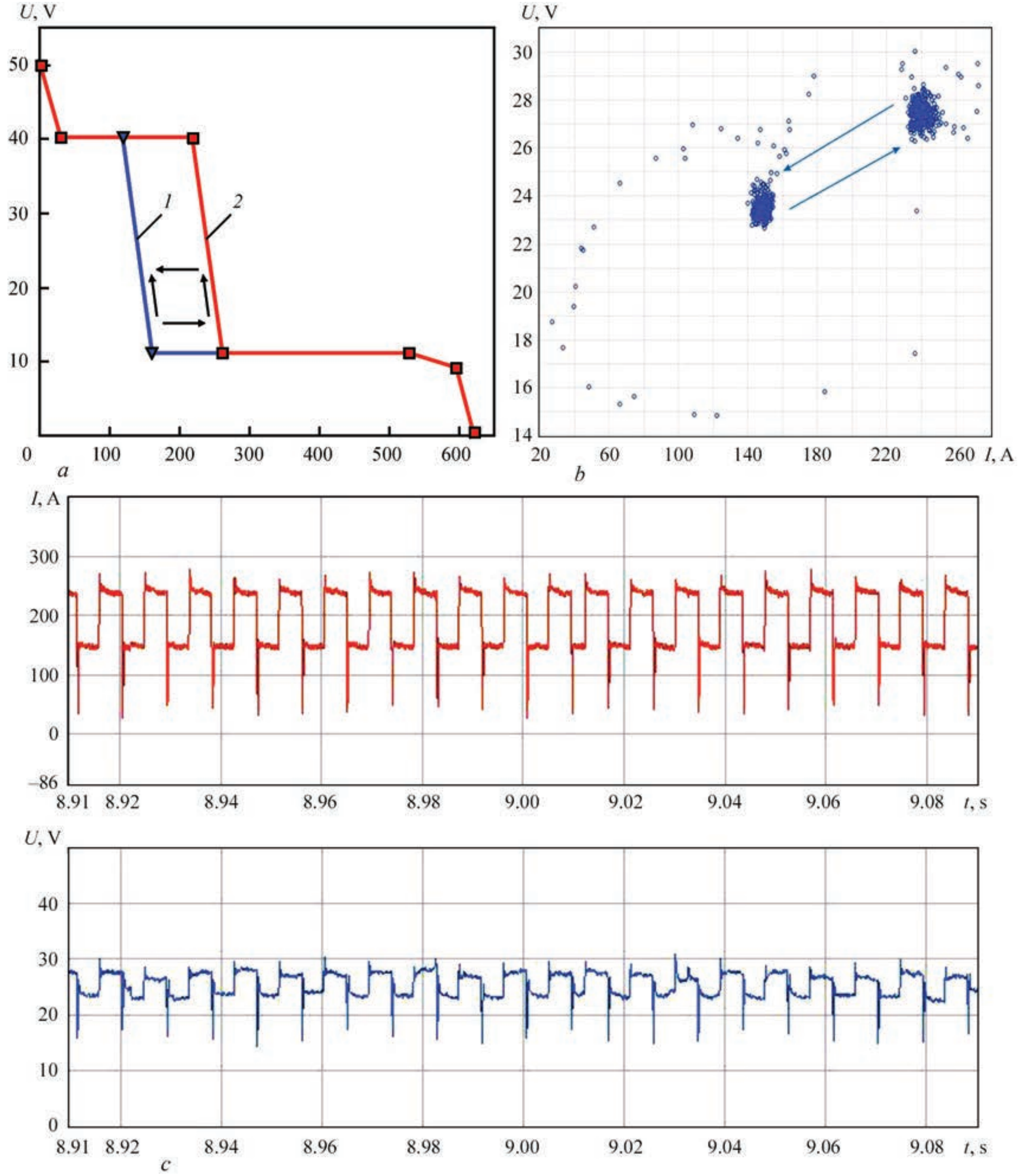


Figure 1. Combination of VACh of power source for realization of a pulsed process of welding (*a*): *1*, *2* — respectively, pause and pulse current; dynamic VACh (*b*) and oscillogram of the process (*c*)

PROCEDURE OF EXPERIMENT

To realize the set task, the power source LET-500 was used. Using additional software, a very flexible adjustment of most of the power source parameters can be performed, including the shape of the output volt-ampere characteristics. The pulsed mode of the source operation allows operating on two such VACh indicating the time of operation of each one (Figure 1, *a*). The falling regions of VACh (*1* and *2*) correspond to the pause and pulse current. During switching between the characteristics, the value of the welding current varies to the corresponding value for the actual characteristic (Figure 1, *b*, *c*).

For the first part of the experiments, the families of volt-ampere characteristics VACh No.1 and VACh No.2 were selected (Figure 2, *a*). The main difference between the families was in a gradual increase in the pause current, shifting the falling area *1* to the left (curve *1*) (VACh No.1). In this case, the position of the curve *2* (VACh No.2) remained unchanged.

In the work, the pulsed-arc process with a frequency $f = 100$ Hz and a duty cycle $C = 2$ was used. The input energy Q for each experiment (Table 1) was calculated by the formula:

$$Q = \frac{60 I_{mean} U_{mean}}{v_w} \eta,$$

where v_w is the welding speed (m/h), $\eta = 0.7$; I_{mean} is the mean welding current, which is calculated by the

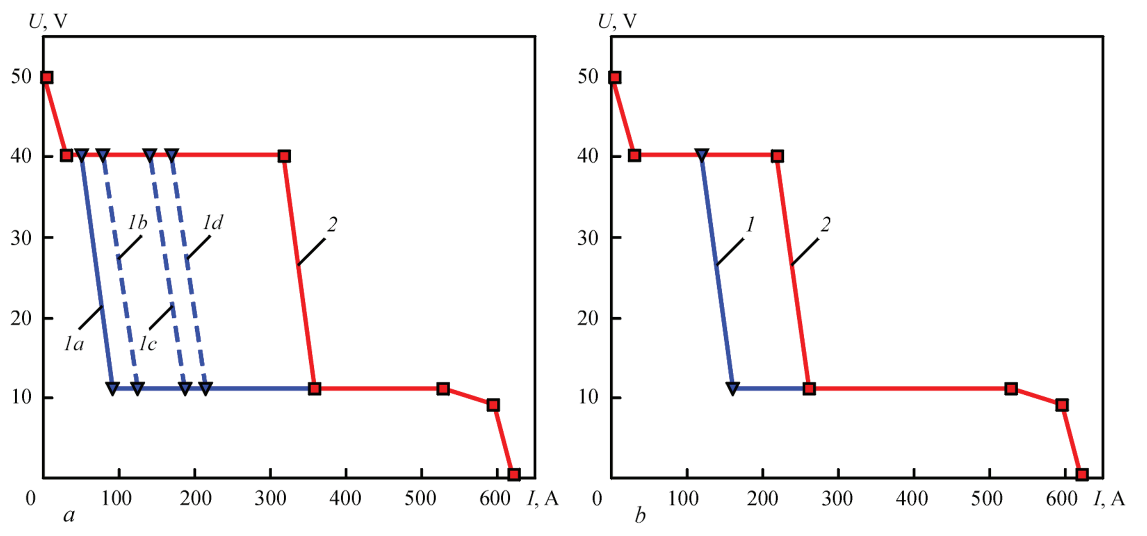


Figure 2. VACh family for PAW performance in order to determine the dependence of geometric dimensions *b*, *h* from: *a* — welding modes I_{mean}, U_{mean}; *b* — frequency *f* of the process (description *1*, *2* see in the text)

formula known for pulsed-arc processes, namely, $I_{mean} = (I_{pulse}\, t_{pulse} + I_{pause}\, t_{pause})/(t_{імпульсу} + t_{pause})$.

In order to determine how frequency *f* of the pulsed-arc process that occurs with short-circuits, affects the geometric characteristics *h* and *b*, the experimental studies were conducted. For this purpose, to the pulsed power source, VACh No.1 and VACh No.2 were introduced (Figure 2, *b*), the welding speed was v_w = 30 cm/min, the feed of welding wire was v_{wire} = 6.4 m/min. After setting up, deposits on the plate at a frequency *f* = 5, 10, 25, 37, 50, 75 and 100 Hz were performed. In order to avoid thermal effect from the preliminary deposition, each subsequent deposition was performed after cooling of the plate to 20 °C. The indicated parameters provided the following welding mode I_{mean} = 202–205 A, U_{mean} = 21.5 V. This, in accordance with the formula, allowed obtaining the heat input at the level *Q* = 6.0–6.2 kJ/cm.

To detect the influence of PAW frequency *f* on the width and microstructure of HAZ of welded joints, the experimental part of the work envisaged carrying out deposits on the plate of 09G2S steel with pulses of 3, 5, 10, 25, 37 and 50 Hz frequency. In order to compare the obtained results, surfacing using the conventional process of mechanized arc welding in a mixture of Ar + CO_2 was additionally performed. To conduct the experiments, the volt-ampere characteristics were selected, depicted in Figure 2, *b*, providing pulsed-arc and conventional (Figure 3) process of welding.

The modes of mechanized welding (I_{mean}, U_{mean}) by the wire Sv08G2S of 1.2 mm diameter in a mixture of Ar + CO_2 for both processes were determined using the computerized information and measuring system IMS 2007 (Table 2). The heat input *Q* for each experiment was determined by the formula.

After the completion of deposits on the plate of 12 mm thickness, the sections for metallographic

Table 1. Received modes of a pulsed-arc process at different positions of VACh No.1

VACh No.1	I_{mean}, A	U_{mean}, V	*Q*, kJ/cm	v_w, cm/min	v_{wire}, m/min
1*a*	187	22	5.760	30.0	6.8
1*b*	200	23	6.440		
1*c*	225	25.4	8.036		
1*d*	230	29.2	9.402		

Table 2. Mechanized welding modes

f, Hz	I_{mean}, A	U_{mean}, V	*Q*, kJ/cm	v_{wire}, m/min	v_w, cm/min	Note
3	203	21.8	6.195	6.4	30.0	PAW
5	203	21.6	6.139			
10	198	22.2	6.153			
25	207	21.1	6.115			
37	198	22.3	6.181			
50	205	21.0	6.027			
–	200	22.1	6.188	6.4	30.0	Stationary

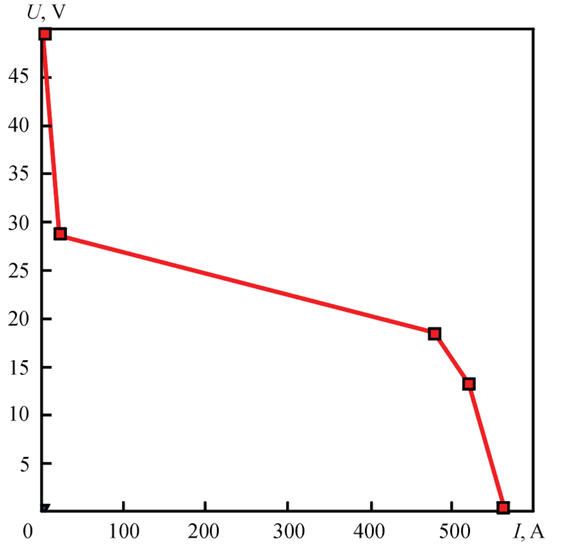


Figure 3. Volt-ampere characteristic of power source to perform mechanized welding by stationary process

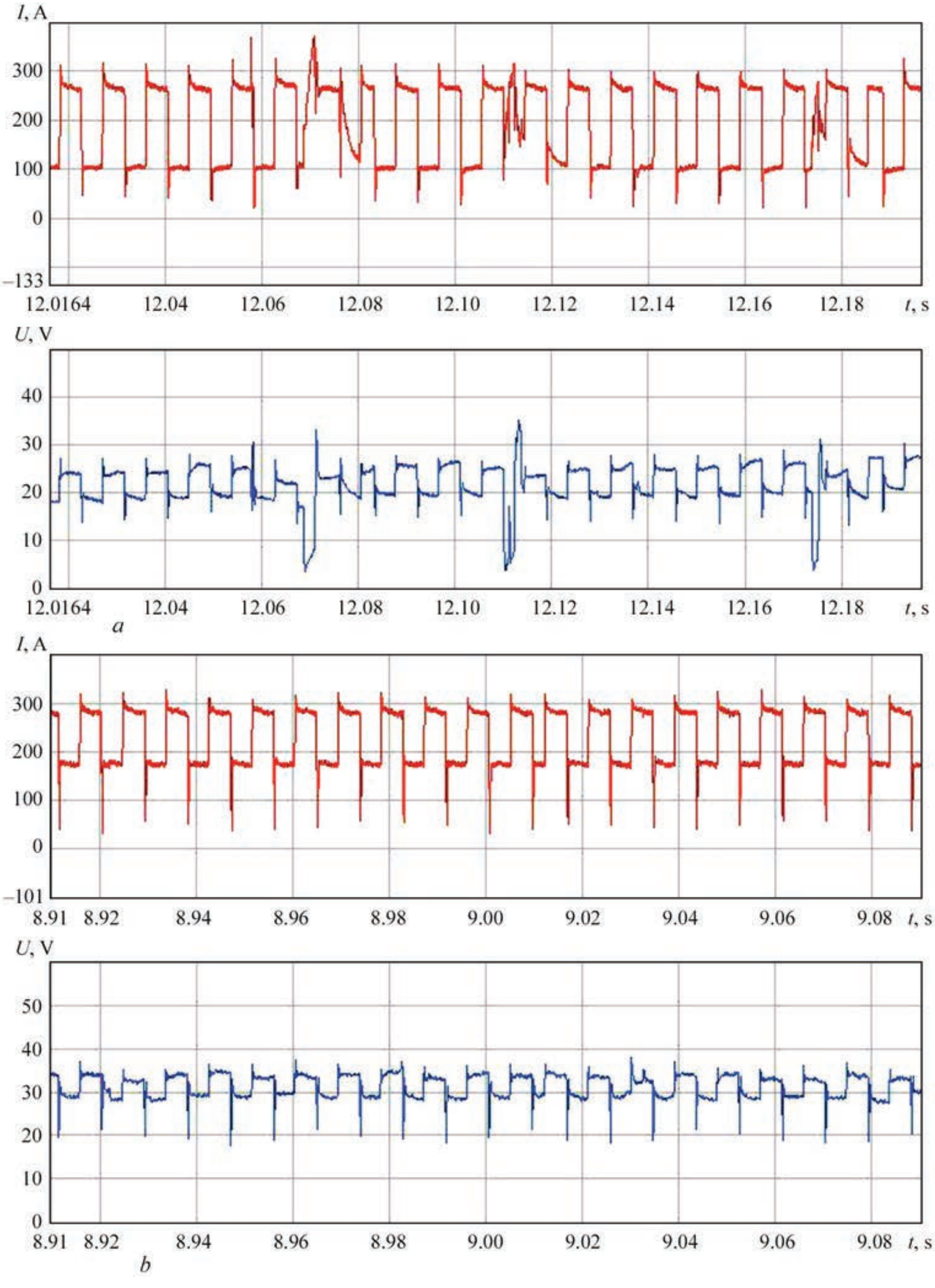


Figure 4. Oscillograms of pulsed-arc processes: *a* — with short circuits (for I_{mean} = 187 A); *b* — without short circuits (for I_{mean} = 225 A)

examinations of weld and HAZ metal were made. The hardness of the HAZ and the weld region was measured on the microhardness meter M-400 LECO.

As a result of data processing from oscillograms, it was found that a gradual increase in the value of the pause current causes an increase in the mean welding current, which increases the power of the process. Given that the rate of welding wire feed remains unchanged, a more intensive melting of the metal on the electrode end and the elongation of an arc gap occur. An increase in the mean welding voltage can be observed. A change in the pulsed-arc process with short circuits on a process without short-circuit is also observed (Figure 4).

At the histograms of the arc voltage, this is reflected by the presence of instant values in the range of $U_{sh.-c}$ = 3–10 V (Figure 5, *a*), which is characteristic for short circuits, and by their absence as compared to PAW on a “long” arc (Figure 5, *b*).

RESULTS OF INVESTIGATIONS AND DISCUSSION

Adjustment of VACh No.1 from the position 1*a* to the position 1*d* leads to an increase in the value of the heat input $Q = f(I_{mean}, U_{mean})$ with the respective changes in geometric sizes and shapes of deposited beads at v_{wire} = const, v_w = const. It was established that an increase in the pause current leads to an increase in U_{mean}, and this is ultimately reflected on the growth

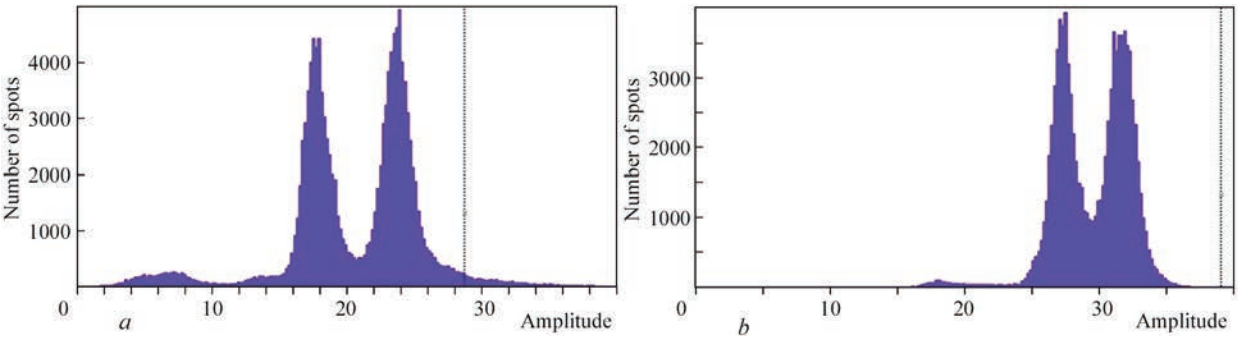


Figure 5. Histogram of instant values of arc voltage at a pulsed-arc process: *a* — with short circuits for I_{mean} = 187 A); *b* — without short circuits (for I_{mean} = 225 A)

in the width of the beads *b* with a corresponding decrease in the penetration depth *h* (Figure 6).

The influence of the heat input $Q = f(I_{mean}, U_{mean})$ of the pulsed process on the mean value of the penetration depth *h* and the width *b* of the beads is shown in Figure 7.

An analysis of the results of measurements of the width of the deposits and the penetration depth showed that an increase in the value of frequency *f* from 5 to 100 Hz does not lead to a change in geometric dimensions. The most significant influence of the frequency *f* affects the amount of ripples of the beads: with an increase in *f* to 100 Hz, the amount of ripples decreases (Figure 8). This is associated with the fact that a rapid switching of the operation of the pulsed power source from VACh No.2, which is responsible for the maximum energy level of the process, to VACh No.1, which determines the minimum energy level, does not lead to a significant cooling of molten metal. The thermal mode of the pool is approaching a quasi-stationary state, which is characteristic of conventional welding with short circuits without a pulsed effect.

Investigation of the effect of the PAW frequency *f* on the width and microstructure of HAZ of welded joints showed that the structure of the deposited weld metal is ferritic-perlitic with separate regions of a preeutectoid ferrite on the boundaries of crystallites. Regarding HAZ, the analysis as in the cases of PAW, as well as in a stationary arc showed that almost the same types of structural components are formed on a region of a coarse grain. Therefore, in general, the structure of this region in all specimens is ferritic-perlitic with different modifications of ferrite: ordered by a second phase, Widmanstätten, polyhedral (Figure 9). In the specimens that were produced during PAW with the frequencies *f* = 37, 50 Hz and by stationary welding mode, the structures of bainite were additionally revealed.

The size of grains in the region of HAZ overheating grows with an increase in frequency *f*. Therefore, for *f* = 3, 5 Hz, grain size number amounts to 7–8 (D_{gr} = 22–30 μm); at *f* = 10 Hz — 7 (D_{gr} = 30 μm); *f* = 25, 37 Hz — 6, 7 (D_{gr} = 30–44 μm). For *f* = 50 Hz and the stationary process of welding, the grain size number amounts to 6 (D_{gr} = 44 μm).

Measurement of microhardness *HV*1 in different zones showed that a gradual increase in frequency *f* does not lead to significant changes in the mean values of microhardness on the region of a coarse grain (Figure 10).

A mean value of microhardness for *f* = 50 Hz is approaching to such that is obtained in welding by a stationary arc. In the analysis of these results, it seems that with an increase in the PAW frequency *f*,

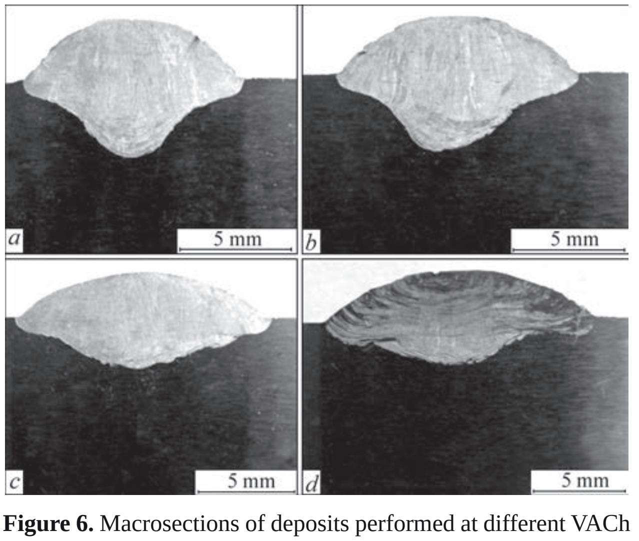


Figure 6. Macrosections of deposits performed at different VACh No.1: *a* — positions 1*a*; *b* — 1*b*; *c* — 1*c*; *d* — 1*d*

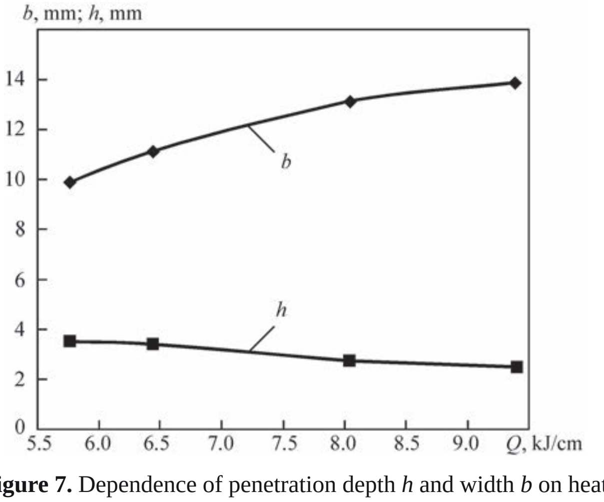


Figure 7. Dependence of penetration depth *h* and width *b* on heat input $Q = f(I_m, U_m)$ of a pulsed process

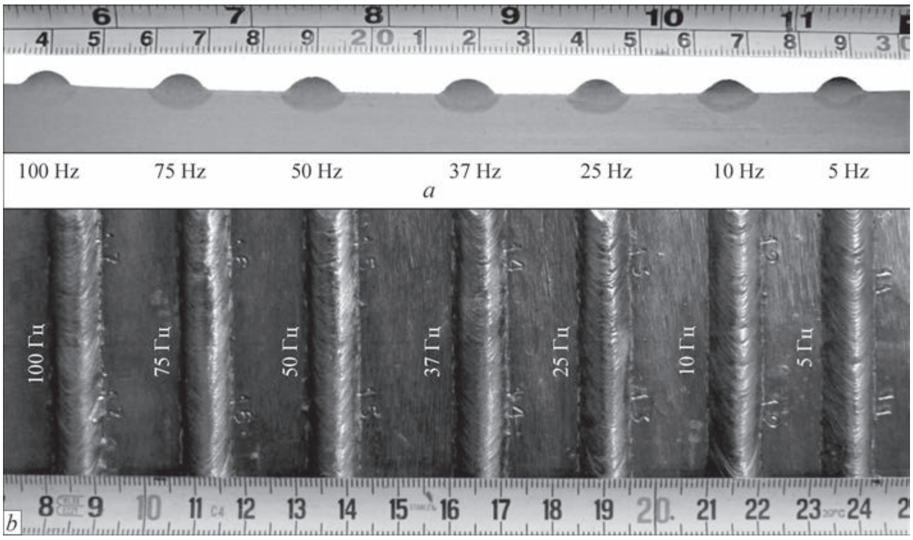
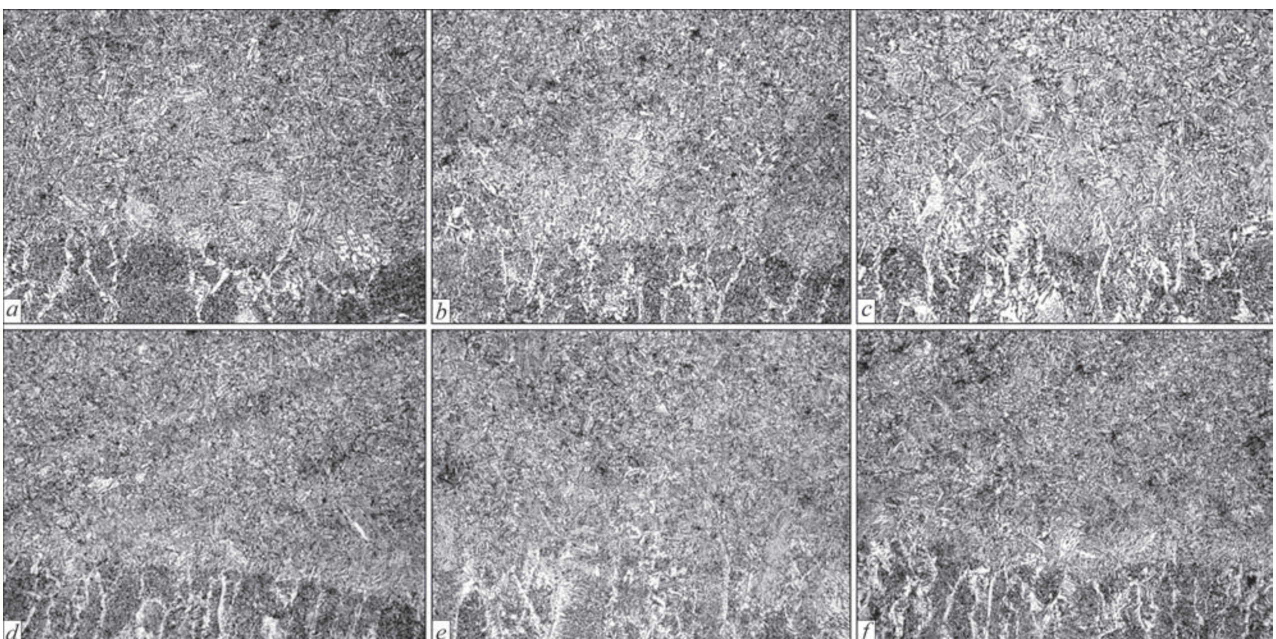


Figure 8. Influence of frequency *f* of a pulsed process on the section of beads (*a*); ripples of deposited metal (*b*)

the effect of impact on the HAZ metal approaches the process of welding with a stationary arc.

In relation to one more index — the width of HAZ, the results of metallographic examinations showed a gradual, slight decrease in the total width of HAZ with an increase in frequency *f* to 50 Hz (Figure 11).

A similar trend is observed also in the region of coarse grains in HAZ. However, as compared to the stationary process of welding, the width of this region decreases more significantly — by 25–30 %. Thus, in the case of welding low-alloy steels, due to the application of technology with a pulsed process, there is a prospect to affect the width of the region of HAZ overheating at different values of frequencies and relatively low values of the heat input *Q* (6.0–6.2 kJ/cm). From a practical point of view, this allows reducing the share of an unfavourable, low-ductile area of overheating, which is important



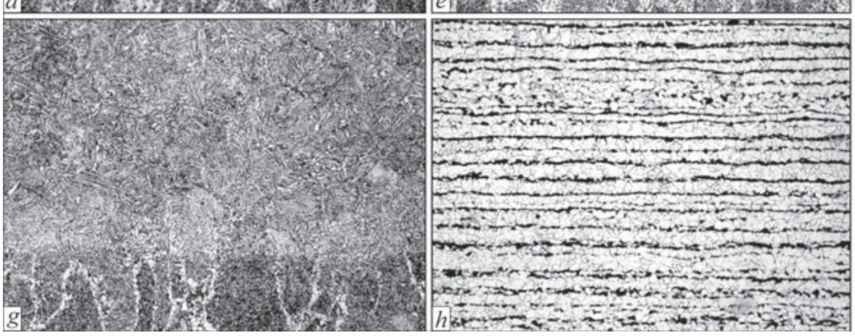


Figure 9. Microstructure (×200) of overheating HAZ region of deposit, produced with varying frequency *f* of a pulsed-arc process: *a* — *f* = 3 Hz; *b* — 5; *c* — 10; *d* — 25; *e* — 37; *f* — 50; *g* — stationary arc; *h* — structure of base metal

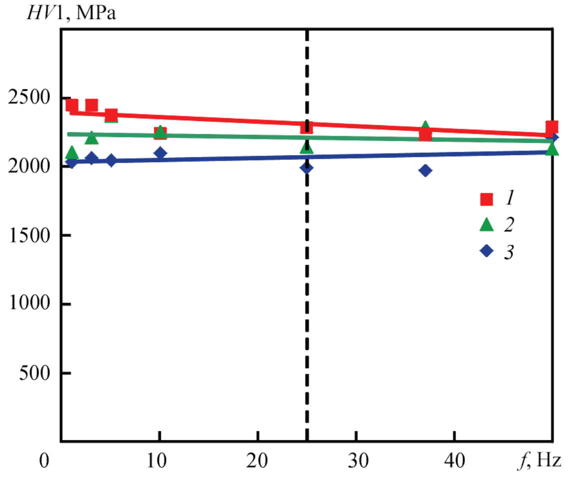


Figure 10. Impact of PAW *f* frequency on the distribution of microhardness *HV*1 in different regions of HAZ: *1* — coarse grain region near the fusion line; *2* — region of coarse grain near the region of recrystallization; *3* — weld near the fusion line

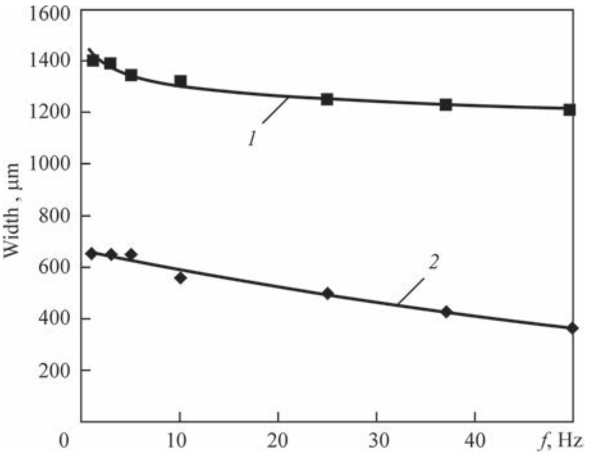


Figure 11. Impact of PAW f frequency on the total HAZ width (*1*) and width of the coarse grain region (*2*) at Q = 6.0–6.2 kJ/cm

for the cases of repair of wall thinnings in the pipes during remelting of the defects in the operating pipeline using mechanized method.

CONCLUSIONS

1. It was established that a gradual increase in the pause current due to the displacement of a falling VACh region at an unchanged rate of electrode wire feed leads to an increase in the arc voltage and, as a consequence, the pulsed-arc process with short circuits changes to the process without short circuits. In this case, an increase in the width of beads by 30–40 % with a corresponding decrease in the penetration depth by 25–30 % is observed.

2. An increase in frequency from 5 to 100 Hz does not affect the geometric parameters of the weld. However, a decrease in ripples is observed.

3. It was shown that a change in the PAW frequency almost does not affect the structural components on the region of coarse grain of HAZ, which also coincide with a specimen, welded applying stationary welding modes. Also no significant changes in the values of the average microhardness on the region of a coarse grain is observed.

4. It was established that an increase in frequency has a direct proportional effect on the size of the grains in the region of HAZ overheating. Thus, as the PAW frequency increases from 3 to 50 Hz, the size of grains in the HAZ overheating region increases from 8 (D_{gr} = 22 μm) to 6 (D_{gr} = 44 μm).

5. It was established that an increase in PAW frequency allows reducing the width of HAZ and the region of a coarse grain. In this case, a decrease in the width of the region of a coarse grain is more significant and reaches 25–30 % at a frequency f = 50 Hz.

REFERENCES

1. Saraev, Yu.N., Makarova, L.I., Kirilova, N.V. et al. (2001) Ways of increase in efficiency of construction, operation and repair of oil and gas equipment and main pipelines on the base of adaptive pulsed technologies of welding and surfacing. *Svarochn. Proizvodstvo*, **5**, 31–37 [in Russian].
2. Mazel, A.G., Tarlinsky, V.D., Shejkin, M.Z. (1979) *Modern methods of fusion welding of main pipelines*. Moscow, Nedra [in Russian].
3. Saraev, Ju.N. (1999) Increase in efficiency of arc welding based on an adaptive algorithm for pulsed control of process energy parameters. In: *Proc. of Int. Conf. LUI Join'99 on Efficient Welding in Industrial Applications (ICEWIA)*, 222–226.
4. Krampit, N.Yu., Krampit, A.G. (2014) Investigation of the process of CO_2 consumable electrode pulsed arc welding. *Vestnik MGTU, Ser. Mashinostroenie*, **5**, 106–112 [in Russian].
5. Knyazkov, A.F., Knyazkov, S.A. (2011) Active control of melting and transfer of electrode metal. *Svarka i Diagnostika*, **4**, 27–32 [in Russian].
6. Verevkin, A.V. (2010) *Increase in efficiency of CO_2 welding of main pipeline fixed joints through the application of pulse power supply of the welding arc*: Syn. of Thesis for Cand. of Tech. Sci. Degree., Barnaul [in Russian].
7. Krampit, M.A., Burakova, E.M., Zubenko, L.N. (2014) Tendencies of development of pulsed methods for welding process control. In: *Proc. of 5th Int. Sci.-Pract. Conf. on Innovative Technologies and Economics in Mechanical Engineering, (22–23 May 2014)*, Vol. 1.
8. Yakushin, B.F., Bakulo, A.V. (2017) On mechanism of weld metal structure formation in pulsed arc welding. *Svarochn. Proizvodstvo*, **9**, 29–35 [in Russian].
9. Manikya Kanti, K., Srinivasa Rao, P., Ranga Janardhana, G. (2013) Optimization of weld bead penetration in pulsed gas metal arc welding using genetic algorithm. *Int. J. of Emerging Technology and Advanced Engineering*, 3(**3**), 368–371.
10. Zhernosekov, A.M., Andreev, V.V. (2007) Consumable electrode pulsed arc welding. *The Paton Welding J.*, **10**, 48–52.
11. Golikov, N.I., Maksimova, E.M., Saraev, Yu.N. (2019) Investigation of the microstructure of the heat-affected zone of low-alloyed steel during pulsed arc welding under conditions of low climatic ambient temperatures. In: *OP Conf. Series: Materials Sci. and Engineering*, 681.
12. Zavdoveev A.V., Poznyakov V.D., Rogante M., et al. (2020) Features of structure formation and properties of joints of S460M steel made by pulsed-arc welding. *The Paton Welding J.*, **6**, 9–13. DOI: https://doi.org/10.37434/tpwj2020.06.02.
13. Zavdoveev, A.V., Poznyakov, V.D., Zhdanov, S.L. et al. (2020) Influence of pulsed-arc welding conditions on change of parameters of weld and HAZ of welded joints and mechan-

ical properties of low-alloy steels. *The Paton Welding J.*, **10**, 21–26. DOI: https://doi.org/10.37434/tpwj2020.12.03.
14. Krampit, A.G., Krampit, N.Yu. (2015) Methods of weld formation control. *Tekhnologii i Materialy*, **2**, 21–26 [in Russian].
15. Golikov, N.I., Sidorov, M.M., Maksimova, E.M., Saraev, Yu.N. (2018) Examination of microstructure of welded joints made under negative temperature conditions. Science — Education — Production: Experience and Prospects of Development. In: *Proc. of 14th Int. Sci.-Tech. Conf. (8–9 February 2018)*, 161–164.
16. Saraev, Y.N., Bezborodov, V.P. (2013) Effect of the energy parameters of the welding process on the structure and properties of welded joints in low-alloy steels. *Welding Intern.*, 2(**9**), 678–680.

ORCID
S.Yu. Maksymov: 0000-0002-5788-0753,
D.M. Krazhanovskyi: 0000-0001-7292-7188,
Yu.A. Shepelyuk: 0000-0002-2912-2648

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR
S.Yu. Maksymov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
E-mail: maksimov@paton.kiev.ua

SUGGESTED CITATION
S.Yu. Maksymov, D.M. Krazhanovskyi, Yu.A. Shepelyuk, S.V Osynska (2022) Effect of parameters of pulsed-arc welding on the formation of weld metal and microstructure of heat-affected zone of 09G2S steel. *The Paton Welding J.*, **3**, 19–26.

JOURNAL HOME PAGE
https://pwj.com.ua/en

Received: 26.01.2022
Accepted: 16.05.2022