DOI: 10.31471/2311-1399-2020-2(14)-61-70

The study of the influence of technological parameters of the impulse process on the formation of the weld metal and the microstructure of the heat-affected zone

[1]S. Yu. Maksymov*, [1]A. A. Gavryliuk, [2]L. S. Shlapak

[1] *E. O. Paton Electric Welding Institute;*
11, Kazemyr Malevych Str., Kyiv, 03650, Ukraine

[2] *Ivano-Frankivsk National Technical University of Oil and Gas;*
15, Karpatska Str., Ivano-Frankivsk, 76019, Ukraine

Received: 16.07.2020 Accepted: 23.07.2020

Abstract

With prolonged operation of metal structures, the likelihood of their mechanical destruction increases. This also applies in many respects to the welded joints of main pipelines. One of the promising ways of solving the issue of increasing their service life is the development of welding methods based on the use of pulse control of process energy parameters. Pulse welding mode allows for controlled heat input into the welded joint zone, control of the electrode metal melting mode, formation of the weld metal structure and heat-affected zone (HAZ).

Two types of metal transfer from the electrode to the weld pool were used in the work: with short circuits and without them, that is, welding was carried out on a "long" arc. At a constant electrode wire feed rate, the welding mode was changed by changing the shape of the current-voltage characteristic of the power source.

It was found that with an increase in frequency, pulsed-arc welding (PAW) by the effect of exposure to the metal, HAZ approaches the process of stationary arc welding. The results of metallographic studies have shown a slight decrease in the total width of the HAZ with an increase in frequency to 50 Hz. A similar trend is observed for the coarse grain area in the HAZ. However, in comparison with the stationary welding process, the width of this section decreases more significantly – by 25–30 %. Thus, when welding pipe steels, due to the use of technology with a pulsed process, there is a prospect of influencing the structure of the overheating section of general relativity at different values of frequencies and, relatively, small values of heat input (6.0–6.2 kJ/cm). From a practical point of view, this makes it possible to reduce the share of unfavorable, low-plastic overheating areas in the HAZ, which is important for repairing thinned pipe walls when defects are melted on an operating pipeline by a mechanized method.

Keywords: *geometric parameters; main pipelines; pulsed-arc welding; structure; technological parameters; welded joint.*

Introduction

Nowadays, due to the technical condition of oil-field equipment and main pipelines, they become objects of increased danger. This circumstance necessitates the application of effective repair methods. With the help of traditional welding methods, it is difficult to solve the main technological problems, they become more complicated, namely: ensuring the possibility of regulation within a wide range of penetration depth, welding with increased slots and in different spatial positions, joining metals and alloys dissimilar in composition, reducing electrode metal spattering, increasing stability ignition of the welding arc and its burning [1].

The main problem in welding fixed joints of main pipelines is to ensure the required quality of root, filling and facing layers and a high level of joint`s mechanical characteristics. It is known that up to 90% of defects detected during quality control of welded joints are associated with defects in the root layers of welded joints: undercuts, lack of penetration, non-metallic inclusions and pores [2]. The main reason for the appearance of these defects, in addition to those associated with poor preparation of joints for welding, is a violation of the welding modes (welding speed, arc voltage, current), as well as their inconsistency with the required values, ensuring the production of high-quality welded ones [3]. Traditionally used manual welding processes can ensure the required quality of welded joints only with careful preparation of the welded joint and the use of high quality materials [4].

The accumulated experience shows that pulse methods for controlling the welding process can solve the following technological problems:

controlled and directed transfer of electrode metal;

the ability to perform welding in all spatial positions and simplify the welding technique;

improvement of the quality of welded joints due to a greater concentration of energy from the heating source and better conditions for primary crystallization;

reduction of losses for waste and splashing [5].

* Corresponding author:
maksimov@paton.kiev.ua

Table 1 – Modes of the pulse-arc process at different positions of VAC no. 1

VAC no. 1	$I_{av.}$, A	U_{av}, V	Q, kJ/cm	v_{weld}, cm/min	v_{wire}, m/min
1*a*	187	22.0	5.760	30.0	6.8
1*b*	200	23.0	6.440		
1*c*	225	25.4	8.036		
1*d*	230	29.2	9.402		

At this time, the relevance of the effective use of pulse welding methods is obvious, since these methods create the most favorable conditions for active control of the melting and transfer of electrode metal, thereby enabling to improve the quality of welding in various spatial positions and obtain a weld with specified properties. PAW provides separate and independent control on the one hand, by melting and transfer of electrode metal and, on the other hand, by melting and crystallization of the molten pool metal [6, 7].

The analysis of the macro- and microstructure of a welded seam has shown that under pulse feeding the weld structure is fine-grained and misoriented, and the mechanical properties of welded joints are higher than in welding with short circuits of the arc gap [8, 9]. The superposition of pulses can significantly increase the intensity and stability of the arc discharge, there are changed hydrodynamic processes in the weld pool and the conditions for its crystallization. A pulse increase in the arc pressure improves the formation of the weld, the bead of the weld becomes fine-grained, and the microstructure is refined due to the impact of electrode metal drops [10, 11]. The results obtained are in good agreement with the previously obtained results, in which the effect of significant refinement of the weld metal structure and the heat-affected zone was established when using pulsed-arc welding with coated electrodes [12, 13].

The purpose of the research is to determine the effect of welding modes and the frequency *f* of the pulsed-arc welding process on the geometric dimensions of the surfacing and structural transformations in the heat-affected zone due to the use of metal transfer from the electrode to the weld pool: with and without short circuits (SC), that is, welding is performed on a "long" arc.

To establish the effect of the welding current on the nature of the welding process and to study the structural components, grain size and microhardness of the heat-affected zone.

Results of researching

For the experiments, there have been selected the groups of volt-ampere characteristics (VAC no. 1 and no. 2), alternately set in pairs into the power supply controller before performing pulse-arc welding (PAW). The main difference between the groups is the gradual increase in the average value of the I_{av} welding current and arc voltage U_{av} of the impulse process. This is achieved by moving the falling section VAC no. 1 (*1a – d*), which is responsible for the value of the minimum welding current, towards VAC no. 2, which determines the value of the maximum welding current (Fig. 1). In this case, the position of the VAC no. 2 remained unchanged.

In the sudy, there were used a pulse-arc process with a frequency f = 100 Hz and a duty cycle C = 2.

The rate of energy input Q for each experiment (Table 1) was calculated by the formula as follows

$$Q = \frac{60\eta I_{av} U_{av}}{v_{weld}} \ . \qquad (1)$$

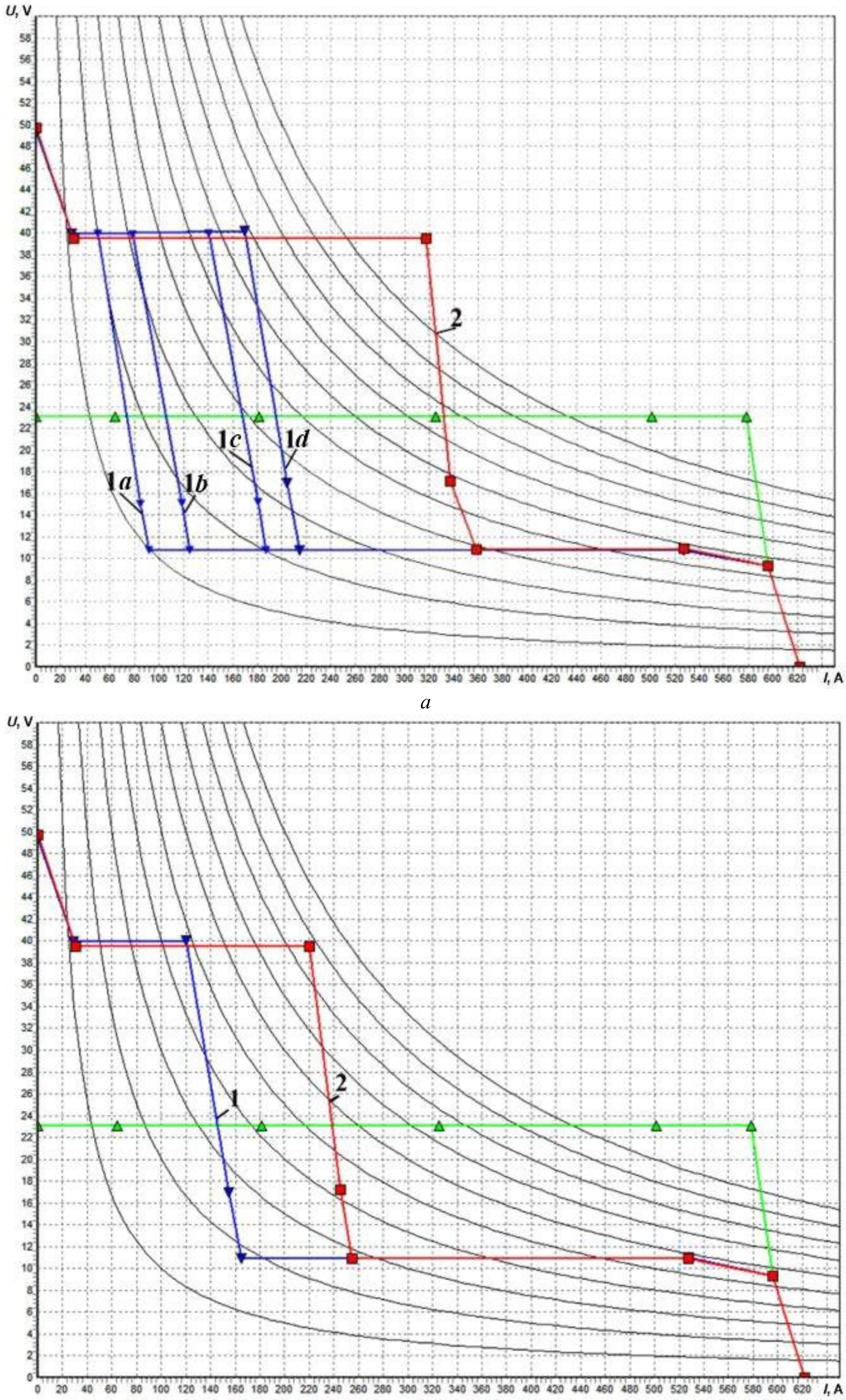
As a result of processing the oscillogram data, it is found that a gradual increase in the value of I_{av} leads to the fact that at v_{wire}= *idem*, the pulse-arc process with short circuits changes to a process without s.c. This is reflected in the arc voltage histograms by the presence of instantaneous values in the range of $U_{s.c}$ = 3–10 V (Fig. 2, *a*), which is typical for short-circuit, and in comparison with the PAW at the "long" arc, by their absence (Fig. 2, *b*).

Regulation of the VAC no. 1 from position 1*a* to position 1*d* leads to an increase in the rate of energy input $Q = f(I_{av}, U_{av})$ with corresponding changes in the geometric dimensions and shape of the weld beads at v_{wire}= *idem*, v_{weld}= *idem*. It has been established that an increase in I_{av} leads to an increase in U_{av}, and this is ultimately reflected in an increase in the width of the beads *b* with a corresponding decrease in the penetration depth *h* (Fig. 3).

The influence of the heat input $Q = f(I_{av.}, U_{av.})$ of the pulse process on the average value of the penetration depth *h* and the width *b* of the beads is shown in Fig. 4.

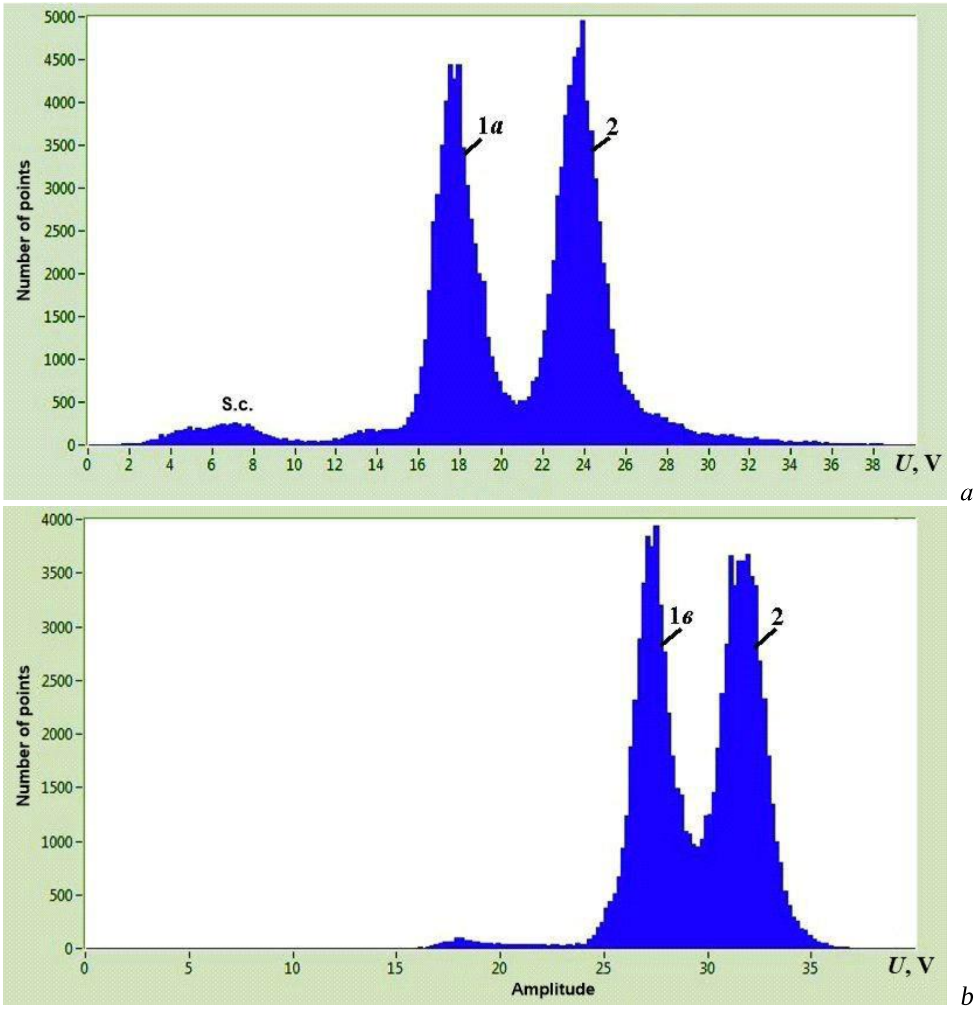
Analysis of the data obtained, oscillograms of welding current and arc voltage, histograms of instantaneous values of these parameters shows the following. With an increase in heat input within Q = 6–10 kJ/cm for a wire with a diameter of 1.2 mm, there is a transition from a process with short circuits to a process without short circuits. In this case, an increase in the value of Q leads to an increase in the width of the surfacing *b* by 30–40 % with a decrease in the penetration depth *h* by 25–30 %.

In order to determine how the frequency *f* of the pulse-arc process, which proceeds with short circuits, affects the geometric characteristics of *h* and *b*, there are carried out experimental studies. For this purpose, the VAC no. 1 and the VAC no. 2 are introduced into the pulsed power supply (Fig. 1, b), which ensured the following mode: $I_{av.}$ = 202–205 A, $U_{av.}$ = 21.5 V, v_{wire}= 6.4 m/min, v_{weld} = 30 cm/min. This, in accordance with (1), made it possible to obtain the heat input at the level of Q = 6.0–6.2 kJ/cm. After adjusting, surfacing was performed on the plate at a frequency of f = 5, 10, 25, 37, 50, 75, 100 Hz. To avoid thermal effects from preliminary surfacing on *h* and *b*, each subsequent



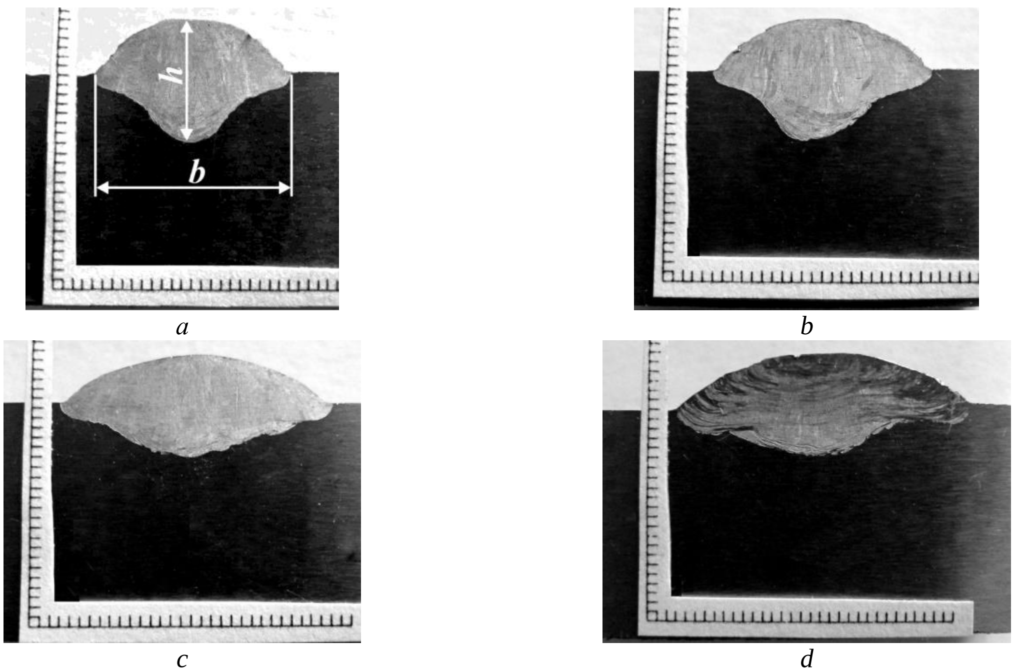
a) welding modes I_{av}, U_{av}; b) frequency f of the process

Figure 1 – Group of VAC for performing PAW in order to determine the dependence of geometrical dimensions *b, h*



a) with short circuits (for I_{av}= 187 A); b) without short circuits (for I_{av}= 225 A)

Figure 2 – Histograms of instantaneous values of arc voltage in the pulse-arc process



a) positions 1a; b) positions 1b; c) positions 1c; d) positions 1d. one division – 0.5 mm*

Figure 3 – Macrosections of surfacing performed at different VAC no. 1

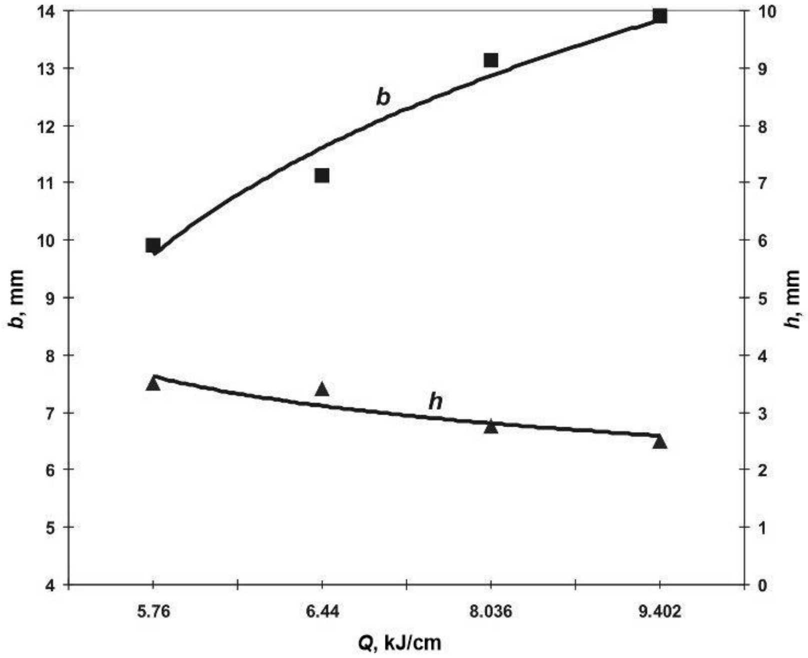
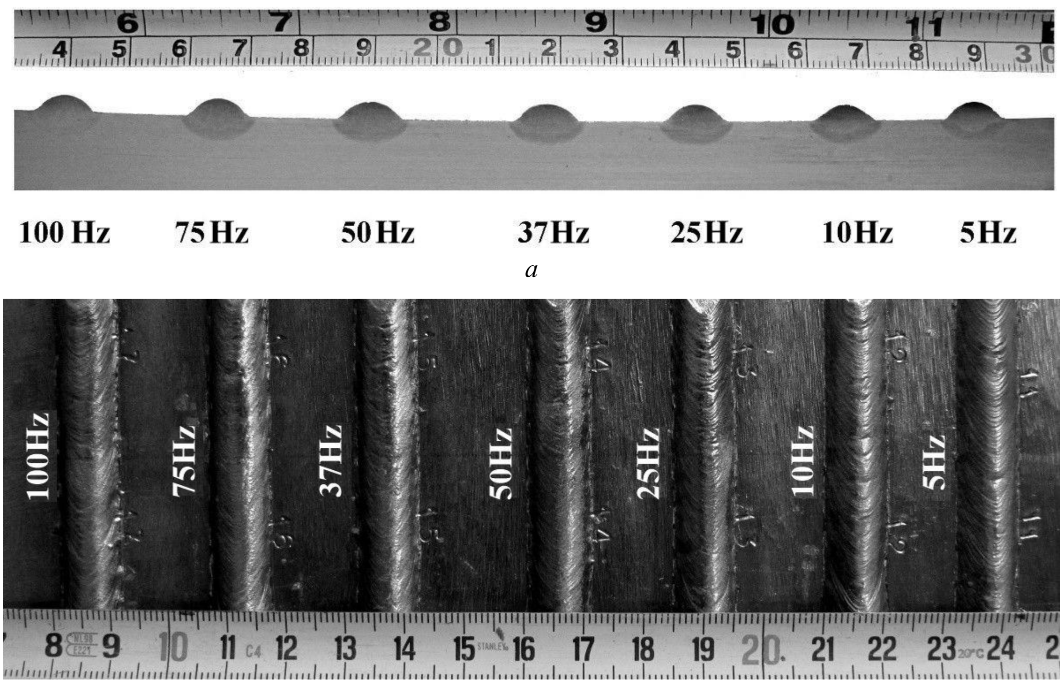


Figure 4 – Dependence of penetration depth *h* and width *b* on heat input $Q = f(I_{av.}, U_{av})$ in a pulse process



a

b

a) section of rollers; b) flaking of the weld metal

Figure 5 – Influence of the frequency *f* of the pulse process on the cross-section of rollers and flaking of the weld metal

surfacing was performed after the plate was cooled to 20 °C.

Analysis of measurement results of the surfacing width *b* and the depth of *h* penetration has shown that an increase in the frequency *f* from 5 to 100 Hz did not lead to a change in the geometric dimensions. The most significant effect of the frequency *f* is reflected on the flakiness of rolls: with an increase in *f* to 100 Hz, the flakiness decreases (Fig. 5). This is due to the fact that a fleeting switching of the operation of a pulsed power supply from VAC no. 2, which is responsible for the maximum energy level of the process, to VAC no. 1, which determines the minimum energy level, does not lead to significant cooling of the molten metal. The thermal regime of the molten pool approaches a quasi-stationary state, which is typical for conventional short-circuit welding without impulse action.

Figure 6 – Current-voltage characteristics of the power source for performing mechanized welding by a stationary process

Table 2 – Modes of mechanized welding

f, Hz	I_{av}, A	U_{av}, V	Q, kJcm	v_{wire}, m/min	$v_{weld.}$, 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

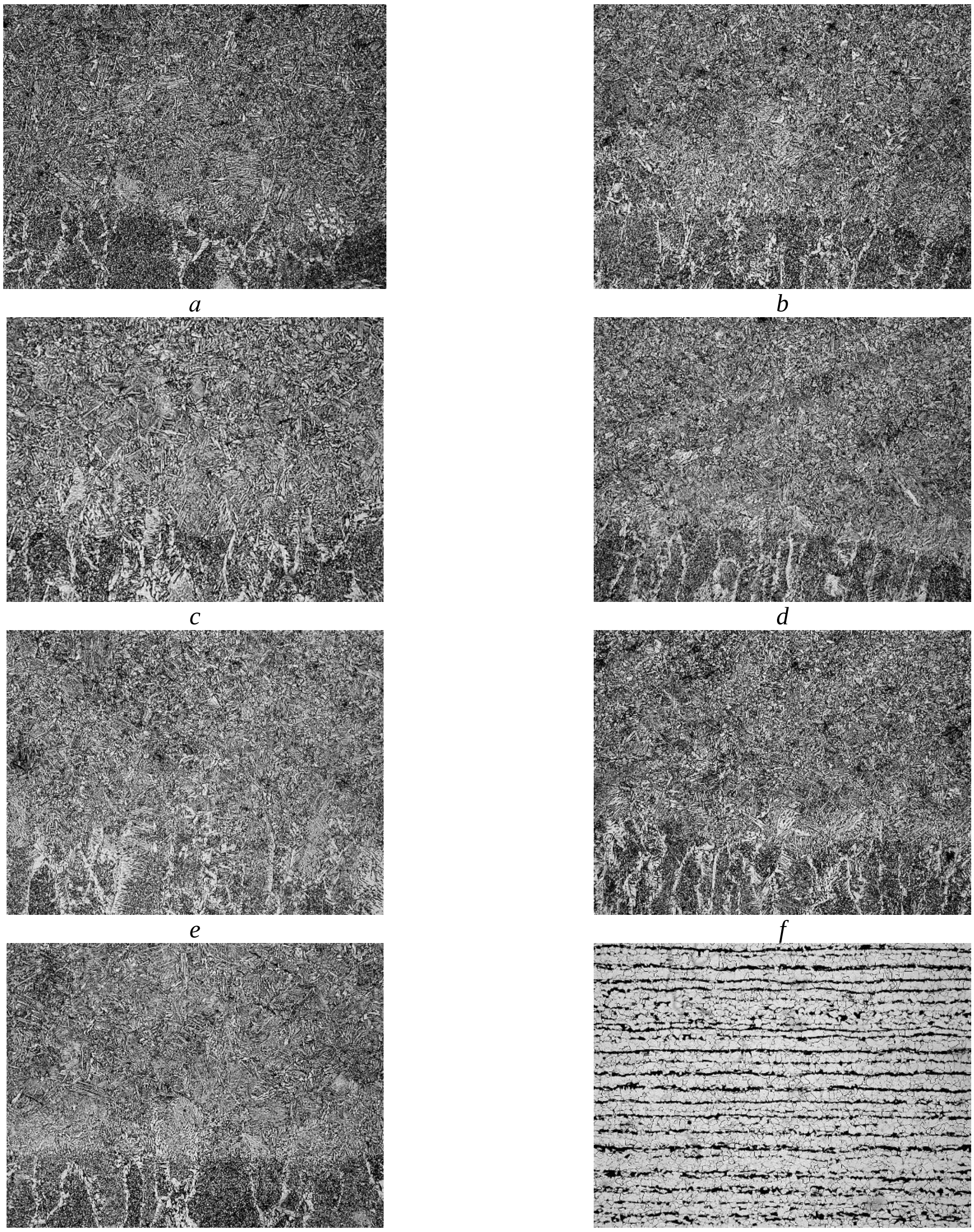
There is also interest in how the frequency f of pulse-arc welding affects the width and microstructure of welded joints HAZ. The experimental part of the work involved surfacing on a 09G2S steel plate with pulses of 3, 5, 10, 25, 37 and 50 Hz. In order to compare the results obtained, welding of metals was additionally performed using a conventional mechanized arc welding process in a mixture of Ar + CO_2.

For the experiments, the current-voltage characteristics were selected, which were put into the controller of the power source providing the pulse-arc (Fig. 1, b) and conventional (Fig. 6) welding process.

The location of the falling sections of VAC no. 1 and VAC no. 2 (Fig. 1, *b)* and their distance between each other are chosen in such a way that the heat input Q for the PAW is equal to the heat input Q for the stationary welding process. Modes of mechanized welding (I_{av}, U_{av}) with Sv-08G2S wire with a diameter of 1.2 mm in a mixture of Ar + CO_2 for both processes are determined using a computerized information-measuring system IMS 2007 (Table 2). The linear energy Q for each experiment is determined by the formula (1).

After surfacing on a 12 mm thick plate, thin sections were prepared for metallographic studies of HAZ and weld metal. The studies were carried out on the 'NEOPHOT-32' optical microscope at various levels of image magnification. The hardness of the HAZ and weld areas was measured on Leco M-400 Hardness Tester.

The studies have shown that the structure of the weld metal is ferrite-pearlite with separate areas of eutectoid ferrite along the crystallite boundaries. With regard to HAZ, the analysis in the cases of both PAW and a stationary arc showed that almost the same types of structural components were formed in the area



a

b

c

d

e

f

g

h

a) f=3Hz; b) f=5Hz; c) f=10Hz; d) f=25Hz; e) f=37Hz; f) f=50Hz; g) stationary arc; h) structure of the base metal

Figure 7 – The structure of the overheating section of HAZ surfacing performed at different *f* frequencies of the pulse-arc process (×200)

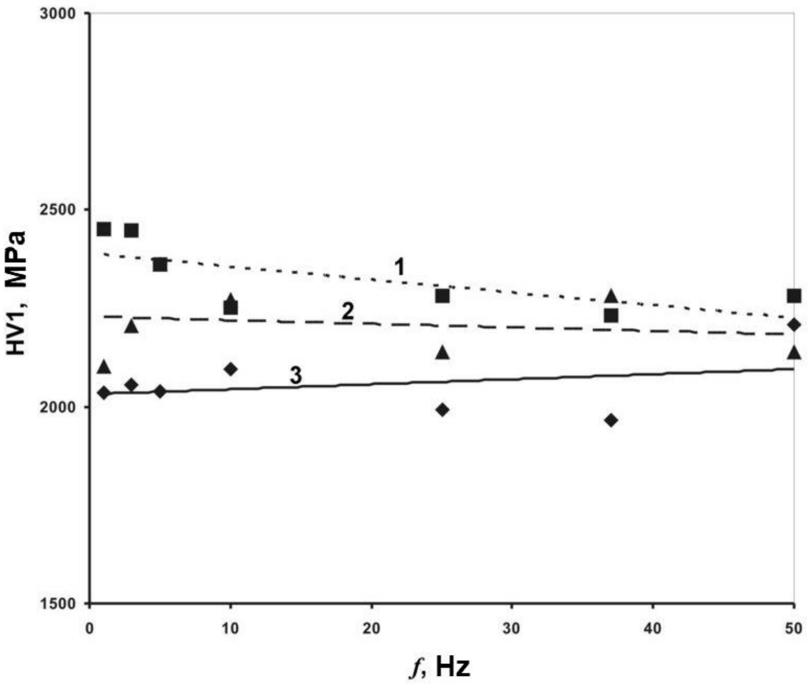
of coarse grain. That is, in general, the structure of this area in all samples is ferrite-pearlite with various modifications of ferrite: ordered second phase, Widmanstätt, polyendric (Fig. 7). Bainite structures were additionally found in the samples obtained by performing the PAW with frequencies f = (37; 50) Hz and stationary welding mode.

The size of grains in the area of overheating of HAZ increases with increasing frequency f. So, for f = 3.5 Hz the grain score is 7–8; for f = 10 Hz – 7; for f = 25 Hz – 6; for f = 37 Hz – 7. For f = 50 Hz and a stationary welding process the grain score is 6.

Measurement of HV1 microhardness in different zones has shown that a gradual increase in the frequency f does not lead to significant changes in the values of the average microhardness in the area of coarse grain (Fig. 8).

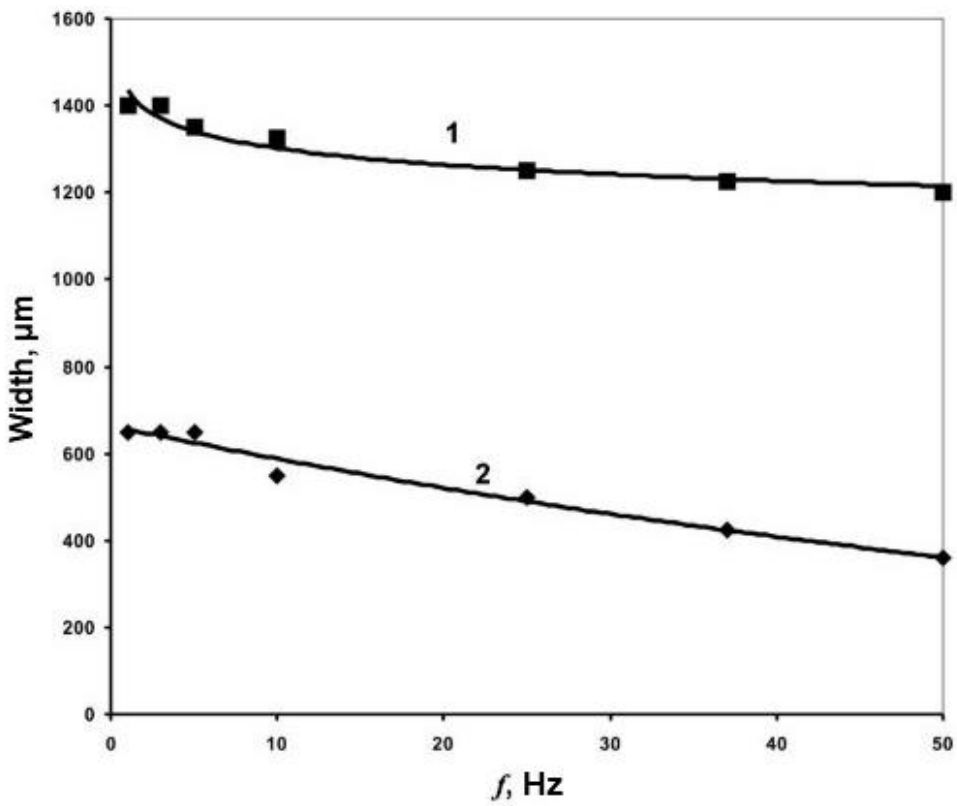
The average value of microhardness for f = 50 Hz approaches the one obtained in stationary arc welding. When analyzing these results, it seems that with an increase in f frequency, the pulse-arc welding by the effect of the influence on the metal with HAZ approaches the process of welding with a stationary arc.

With regard to another indicator – the width of HAZ – the results of metallographic studies have shown a gradual, insignificant decrease in the total width of HAZ with an increase in f frequency to 50 Hz (Fig. 9).



1 – the section of a coarse grain at the fusion line; 2 – the section of a coarse grain near the section of recrystallization; 3 – the weld at the fusion line
** – 1 Hz corresponds to the stationary welding with short-circuit*

Figure 8 – The influence of the frequency of PAW on the distribution of HV1 microhardness in different sections of HAZ



(1) and the width of the section of a coarse grain (2) at Q = 6.0 – 6.2 kJ/cm.
** – 1 Hz corresponds to stationary welding with short-circuit.*

Figure 9 – The influence of the PAW frequency *f* on the total width of the HAZ

ISSN 2311—1399. Journal of Hydrocarbon Power Engineering. 2020, Vol. 7, Issue 2

A similar tendency is observed for a coarse grain section in the HAZ. However, in comparison with the stationary welding process, the width of this section decreases more significantly – by 25–30 %. Thus, during the process of welding pipe steels, due to the application of technology with a pulsed process, there is a prospect of influencing the structure of the HAZ at different frequencies and relatively small values of heat input Q (6.0–6.2 kJ/cm). From a practical point of view, this enables us to reduce the proportion of unfavorable, low-plastic overheating zone the HAZ, which is important for cases of repairing thinned pipe walls when defects are melted mechanically on an operating pipeline.

Conclusions

It has been established that a gradual increase in the average value of the welding current at a constant feed rate of the electrode wire leads to an increase in the arc voltage and, as a consequence, the pulse-arc process with short circuits changes to a process without short circuits. In this case, an increase in the width of rollers is observed with a corresponding decrease in the depth of penetration.

With an increase in heat input within Q = 6–10 kJ/cm for a wire with a diameter of 1.2 mm, there is a transition from a process with short circuits to a process without SC. In this case, an increase in the value of Q leads to an increase in the width of the surfacing by 30–40 % with a decrease in the penetration depth by 25–30 %.

An increase in frequency from 5 to 100 Hz does not lead to a change in geometric dimensions.

It has been shown that, both in the PAW and in the stationary arc, in the area of a coarse grain of the HAZ, there are formed practically identical types of structural components – a ferrite-pearlite with various modifications of ferrite: ordered by a second phase, Widmanstätt and a polyandric one. Bainite structures are additionally found in the samples obtained by performing the PAW with frequencies of f = 37–50 Hz and a stationary welding mode.

The size of grains in the HAZ increases with increasing frequency. So, for f = 3.5 Hz, the grain point is 7–8; at f = 10 Hz – 7; f = 25–37 Hz – 6, 7. For f = 50 Hz and a stationary welding process, the grain point is 6.

Measurement of the microhardness HV1 in different HAZ has shown that a gradual increase in frequency has not led to significant changes in the values of the average microhardness in the area of a coarse grain. The average value of microhardness at f = 50 Hz approaches the one obtained in stationary arc welding.

The total width of the HAZ decreases insignificantly with increasing frequency f to 50 Hz, and the decrease in the width of the coarse grain area is more significant – by 25–30 %.

References

[1] Saraev, YuN 2001, 'Ways to Improve the Efficiency of Construction, Operation and Repair of Oil and Gas Field Equipment and Main Pipelines Based on Adaptive Pulse Welding and Surfacing Technologies', *Welding production*, vol. 5, pp. 31–37.

[2] Mazel, AG, Tarlinsky, VD, Sheikin, MZ et al. 1979, *Modern Methods of Welding Main Pipelines by Fusion*, Nedra, Moscow. [in Russian]

[3] Saraev, Yu,. Bezborodov, VP & Nikonova, IV 2009, 'Structure and Properties of Welded Joints Zones Obtained by Adaptive Pulse-Arc Welding Methods', *Resource and diagnostics of materials and structures:* proceeding Russian Sci. Tech. Conf., Yekaterinburg, May 26–28. [in Russian]

[4] Saraev, YuN 1999, 'Increase in efficiency of arc welding based on an adaptive algorithm for pulsed control of process energy parameters', *Welding Conference LUI Join'99 Int. Conf. on Efficient Welding in Industrial Applications (ICEWIA)*, pp. 222–226.

[5] Krampit, NYu & Krampit, AG 2014, 'Investigation of the Process of Pulsed-Arc Welding with a Consumable Electrode in Carbon Dioxide', *Bulletin of the Bauman MSTU, Ser. 'Mech. Engineering'*, vol. 5, pp. 106–112.

[6] Knyazkov, AF & Knyazkov, SA 2011, 'Active Control of Melting and Transfer of Electrode Metal', *Welding and diagnostics*, vol. 4, pp. 27–32.

[7] Yakushin, BF & Bakulo, AV 2017, 'On the Mechanism of Weld Metal Structure Formation in Pulse-Arc Welding', *Welding production*, vol. 9, pp. 29–35.

[8] Verevkin, AV 2010, 'Increasing the Efficiency of Co2 Welding of Pipelines Fixed Joints Due To the Application of Pulsed Power Supply of the Welding Arc', *Dissertation abstract for the PhD Degree*, Barnaul, p. 20.

[9] Krampit, MA, Burakova, EM & Zubenko, LN 2014, 'Trends in the Development of Pulsed Methods for the Welding Process Control', *Innovative technologies and economics in mechanical engineering*: proceedings of the V Int. Sci. & Pr. Conf., May 22–23.

[10] Knyazkov, AF & Knyazkov, SA 2011, 'Active Control of Melting and Transfer of Electrode Metal', *Welding and diagnostics*, vol. 4, pp. 27–32.

[11] Krampit, AG & Krampit, NYu 2015, 'Methods for Controlling the Formation of a Weld', *Technologies and materials*, vol. 2, pp. 21–26.

[12] Golikov, NI, Sidorov, MM, Maksimova, EM & Saraev, YuN 2018, 'Investigation of Welded Joints Microstructure Made Under Negative Temperatures', *Science – education – production: Experience and development prospects*: Bulletin of the XIV Int. Sci. Tech. Conf., February 8–9, pp. 161–164.

[13] Saraev, YN & Bezborodov, VP 2013, 'Effect of the Energy Parameters of the Welding Process on the Structure and Properties of Welded Joints in Low-Alloy Steels', *Welding International*, vol. 27, no. 9, pp. 678–680.

УДК 621.791.75

Дослідження впливу технологічних параметрів імпульсного процесу на формування металу зварного шва та мікроструктуру зони термічного впливу

[1]С. Ю. Максимов, [1]А. А. Гаврилюк, [2]Л. С. Шлапак

[1] *ІЕЗ ім. Е. О. Патона;*
вул. Каземира Малевича; 11, м. Київ, 03650, Україна

[2] *Івано-Франківський національний технічний університет нафти і газу;*
вул. Карпатська, 15, м. Івано-Франківськ, 76019, Україна

При тривалій експлуатації металевих конструкцій збільшується вірогідність їх механічного руйнування. Це значною мірою стосується і зварних з'єднань магістральних трубопроводів. Одним з перспективних шляхів розв’язання питання підвищення терміну їх експлуатації є розробка методів зварювання, заснованих на використанні імпульсного керування енергетичними параметрами процесу. Імпульсний режим зварювання дозволяє здійснювати регульоване тепловкладення в зону зварного з'єднання, керувати режимом плавлення електродного металу і формуванням структури металу шва та зони термічного впливу (ЗТВ).

В роботі застосовувалося два види переносу металу з електроду в зварювальну ванну: з короткими замиканнями та без них, тобто виконувалось зварювання на "довгій" дузі. При постійній швидкості подачі електродного дроту режим зварювання змінювали шляхом зміни форми вольт-амперної характеристики джерела живлення.

Встановлено, що зі збільшенням частоти імпульсно-дугове зварювання за ефектом впливу на метал ЗТВ наближається до процесу зварювання стаціонарною дугою. Результати металографічних досліджень показали незначне зменшення загальної ширини ЗТВ з підвищенням частоти до 50 Гц. Подібна тенденція спостерігається і для ділянки крупного зерна в ЗТВ. Проте у порівнянні із стаціонарним процесом зварювання, ширина цієї ділянки зменшується більш суттєво – на 25–30 %. Таким чином, у разі зварювання трубних сталей за рахунок застосування технології з імпульсним процесом є перспектива впливати на структуру ділянки перегріву ЗТВ при різних значеннях частот і, відносно, малих значеннях погонної енергії (6.0–6.2 кДж/см). З практичної точки зору це дозволяє зменшити в ЗТВ частку несприятливої, малопластичної ділянки перегріву, що важливо для випадків ремонту стоншень стінок труб під час заплавлення дефектів на діючому трубопроводі механізованим способом.

Ключові слова: *геометричні параметри, зварне з’єднання, імпульсно-дугове зварювання, магістральні трубопроводи, структура, технологічні параметри.*