Stability of the electric arc process during welding has been investigated in this study. A weld seam is produced in 2–4 seconds only, so the quality of connection directly depends on the stability of welding arc burning. The features of the electric arc process are determined by a combination of welding mode parameters: current, welding duration, lifting height, and preliminary rod departure. Establishing the mode parameters that enable stable arc burning is a complex practical task, solving which by the selection method does not warrant the optimal result.

This paper reports results of investigating the welding of A500C reinforcing bars with a drawn arc in flux. The values of the coefficients of variation in the current and voltage, obtained by statistical processing of the welding arc oscillograms, were chosen as a criterion for quantitative assessment of the stability of the electric arc process. It was established that in the entire range of the studied modes, that is, the electric arc process is stable. The plots of variation coefficients depending on the welding current have extrema that correspond to the most stable welding mode. It is this feature of the variation coefficient function that makes it possible to determine the optimal value for the welding current.

The influence of the welding mode parameters on the weld formation process was investigated. The resulting regression dependences enable predicting the volume of molten metal and, as a result, the geometric dimensions of the weld.

Based on the study's results, an engineering methodology for searching for optimal welding mode parameters was devised. The welding mode parameters for reinforcing bars with a diameter of 16 mm were calculated. The established modes were tested when welding a batch of control samples in the amount of 10 pieces; the result is that the geometric dimensions and shape of the welds meet the requirements from DSTU B V.2.6-169:2011

Keywords: drawn arc, welding stability, reinforcing bar, variation coefficient, mode optimization

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DETERMINING THE IMPACT OF WELDING PARAMETERS ON THE ARC STABILITY OF DRAWN ARC SUBMERGED WELDING FOR REINFORCING RODS A500C

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1. Introduction

The production of steel-reinforced concrete structures is an important element in the construction of marine, military, and civil infrastructure facilities. The manufacture of such structures involves the use of various technologies for welding anchor rods with sheet and beam structures. The most commonly used are rods with a diameter of 16…22 mm.

Considering that the number of such rods per square meter reaches 40 pieces, the main requirement is to ensure consistently high quality of the connection, which is not possible without technological stability of the welding process. From an economic point of view, welding a large number of rods requires maximum productivity of the welding process at the minimum cost of consumables.

Among the existing techniques, electric arc welding of studs with an extended arc is the most effective in terms of productivity and does not require additional welding materials, which has led to its widespread use. This welding technique is known as welding process 783 according to the DSTU EN ISO 4063:2022 standard. The technology for welding anchor rods with a diameter of 12…24 mm involves the use of specialized ceramic rings to protect the welding zone from the influence of the external environment and forced formation of the weld.

The equipment and technology designed by Nelson Bolzenschweiss-Technik Gmbh & Co. KG [1] ensure the reliability of arc excitation, the repeatability of welding parameters and, as a result, the technological stability of the welding process. Quality assurance control of welded joints during arc welding of rods can be strengthened through the use of quality monitoring systems [2] based on neural networks, or using sophisticated equipment [3, 4].

But this technology, along with obvious advantages, has significant disadvantages:

– limited range of anchor rods suitable for welding;
– high price of flexible anchors;
– necessity of using ceramic rings.

As a replacement for Nelson anchors, we propose using rods made of class A500C reinforcement. Reinforcing steel has higher mechanical strength indicators compared to the metal of Nelson anchors, which makes it possible to provide greater shear resistance during the operation of a steel-reinforced concrete structure. According to product quality certificates, A500C reinforcement has an average of 10% higher temporary resistance and yield strength indicators (650 MPa versus 590 MPa, 570 MPa versus 510 MPa, respectively).

A500C class reinforcement rods are a cheaper substitute for flexible Nelson anchors, but the ribbed reinforcing rod significantly complicates the use of forming rings and reduces the effectiveness of protecting the welding zone from environmental influences. To overcome this problem, a technology using flux to protect the welding zone was introduced in the 1970s. However, the old rod movement tools and process control systems were too complex and unreliable. In addition, they did not provide the necessary range of adjustment of welding parameters, so the development of this technology was suspended. The design of welding equipment, which is currently mass-produced for the 783 technique, also does not make it possible to weld reinforcing rods under flux. To solve this problem, a pneumatically driven gun design and an electronic welding cycle control unit were proposed [5, 6]. The use of such equipment enables further scientific research into the process and development of innovative industrial technology for submerged arc welding of anchor rods from A500C class reinforcement.

Thus, the economic feasibility of using reinforcing bars for anchoring concrete determines the relevance of studying the features of the electric arc process during their welding. Enabling high technological stability with a minimum percentage of defects will make it possible to introduce a promising technology into serial production with a positive economic effect.

2. Literature review and problem statement

In [7], the results of studies on the influence of changing the mode parameters on the penetration depth of the welded joint are reported. The CCD central composition plan was used as an experimental design scheme. 31 experiments were conducted, during which 5 levels of influence of the main variable factors – welding mode parameters were investigated. The welding current strength was changed in the range of 450...650 A, welding time – 0.25...0.55 s, the preliminary rod flight – 1...3 mm, the rod lifting height – 1.5–3.5 mm. Ref sponse surface analysis revealed that the penetration depth is mainly influenced by the welding current strength. The second parameter in order of importance is welding time. An analytical relationship between the change in the mode parameters and the penetration depth was established. However, the results of the study do not take into account that the quality of the welded joint is a complex value, and limiting the quality assessment only to the penetration depth is insufficient. For example, during welding of high-alloy steels and alloys, a change in the grain structure of the weld seam due to heating can reduce the mechanical strength of the joint while maintaining a sufficient penetration depth. This is the conclusion reached by the authors of the work [8], who performed modeling of the influence of a change in current in the range of 350...500 A and welding time – 0.125...0.300 s on the microstructure and mechanical properties of the welded joint. Using the finite element method (FEM), 2D and 3D structural analyses were performed in the DEFORM software package. The optimal welding mode parameters found in this way were confirmed by metallographic studies and mechanical tests of control samples. It was shown that a change in current strength and welding time lead to a change in the microstructure of the welded joint and, as a result, its mechanical properties.

A similar result was reported in the study on extended arc welding of aluminum alloys AA6061 and AA5086 [9]. It was shown that with a change in current (200–400 A) and welding time (0.1–0.7 s) the mechanical strength of the joint changes. The microstructure of both the weld itself and ZTV of the joint is described in detail.

However, in [8, 9], the question of finding an analytical dependence of the influence of a change in current and welding time on the microstructure and strength of the welded joint remained unsolved. Because of that, the practical use of the results of the indicated works is significantly limited.

The study on the influence of mode parameters on the welding process was approached more systematically in [10]. Unlike [7], the authors investigated the full range of mechanical properties of the welded joint in accordance with the requirements of EN ISO 14555. Microstructure studies were performed on all control samples, and not only on the sample with the highest strength indicators, as in [8].

In study [10], the influence of the welding mode parameters within the appropriate limits was examined: welding current (500–800 A), welding time (0.1–0.4 s), preliminary rod flight (1–4 mm), rod lifting height (1.5–3.0 mm). The results of 16 experiments were analyzed using the Taguchi method. It was shown that the welding current and welding time have the greatest influence on the strength of welded joints. At the same time, if the current does not correspond to the welding time, the mass transfer process and the formation of the weld are disrupted. That is, it has been proven that not only the absolute values of the mode parameters are important, but also the balance between them.

Review of the literature [7–10] demonstrates that the technological process of extended arc welding is characterized by a large number of mode parameters, the main ones of which are welding current, welding time, preliminary rod flight, rod lifting height. Based on this, the search for the optimal value of the welding mode parameters is an important applied scientific task.

A significant drawback of earlier studies is the use of the average value of the welding current, without taking into account the fluctuations of the instantaneous value of this parameter. There are also no studies on the influence of welding arc voltage on the formation of the weld. Thus, sharp fluctuations in the welding current and voltage, which are imperceptible when analyzing the average value of these values, can affect the processes of mass transfer and formation of the weld.

The process of extended arc welding differs significantly from most traditional arc welding methods. The main difference is the very short welding cycle, during which the arc length changes technologically during combustion. A sharp change in welding current and voltage, which are imperceptible when analyzing the average value of these values, can affect the processes of mass transfer and weld formation.

To ensure high stability of the short-term welding process, a method of submerged arc welding was proposed. The idea of using flux for extended arc welding has been previously studied.

In [11], the effect of adding components with low ionization potential, such as Al_2O_3, on the stability of arc combustion was studied. Using high-speed video recording, the mechanism of arc migration during welding of hollow rods was shown. However, the research methodology used in [11] is not suitable for studying the process of arc combustion under a layer of flux that completely covers it.

An option to overcome these difficulties was the use of high-speed video and X-ray methods [12, 13], but their implementation requires very complex and expensive equipment.

Another way to study the process of arc burning under flux is to use ready-made mathematical models with subsequent verification of the obtained data by conducting laboratory tests. A detailed mathematical model of the process of welding under flux is given in [14]. When building a mathematical model, the authors started from the invariance of the length of the arc gap, as in automatic welding under flux. This approach does not correspond to the technique of welding with a drawn arc.

To overcome the above-described difficulties, we propose using the research methodology described in [15]. The stability of the submerged arc welding process was studied using high-speed oscillography of the electrical parameters of the welding arc. It was shown that the deviation of the instantaneous values of current and voltage from the average value is the criterion of stability, and not just the analysis of the average value, as in [7–10]. The use of such an approach will make it possible to move away from the need for direct visual observation of the arc burning under the flux, but at the same time will provide objective indicators of the stability of the arc process.

Thus, there are a number of unresolved issues in the study of submerged arc welding. It should be noted here that the issue of the stability of the electric arc process of welding reinforcing bars under conditions of technological change in the length of the submerged arc has also not been studied yet.

All this allows us to state that it is advisable to conduct a study on the technological stability of the process of welding reinforcing bars with a submerged arc. Determining the quantitative characteristics of stability and devising a methodology for finding the optimal parameters of the welding mode is a key point of our study, the results of which will enable industrial use of the innovative technology of welding anchor bars.

3. The aim and objectives of the study

The purpose of our study is to identify the influence of parameters of the welding mode of reinforcing bars with a submerged arc on the stability of the electric arc process. This will make it possible to introduce the technology of welding reinforcing bars into serial industrial production.

To achieve the goal, the following tasks were set:

– to investigate the features of the formation of a weld seam when welding anchor bars from reinforcing steel;

– to identify and investigate factors that negatively affect the stability of the electric arc process;

– to perform a quantitative assessment of the technological stability of the electric arc process;

– to devise an engineering methodology for determining the optimal parameters for the welding mode of anchor bars.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of research is the stability of the electric arc process during extended arc welding under flux of a ribbed reinforcing bar.

The hypothesis of the research is that the stability of the electric arc process during welding allows for effective and predictable control of weld formation.

Assumptions adopted:

– stability of the short-term welding process can be increased by ensuring reliable arc excitation through the programmed operation of the welding power source;

– using a flux containing components with a low ionization potential will increase the stability of extended arc welding.

Simplifications accepted: the cross-section of the reinforcing bar practically does not affect the characteristic features of the electric arc process since the area of the anode spot of the arc is much smaller than the cross-sectional area of the bar.

4. 2. Research materials

The following materials were used in the study (Table 1):

– 10 mm thick plates made of S355NL steel according to EN ISO 10025-3;

– 16 mm diameter reinforcing bars of class A500C according to DSTU 3760-98;

– OK Flux 10.71 welding flux according to EN ISO 14174.

Table 1

Chemical composition of the test materials, wt %

Grade	C	Si	Mn	P	S	Fe
A500C	0.2	0.12	0.62	0.012	0.016	base
S355J2+N	0.1	0.21	1.25	0.014	0.008	base

The selected brand of welding flux according to the quality certificate contains: 15% CaF_2; Al_2O_3 + 34% MnO; SiO_2 + 21% TiO_2; 24% (CaO + MgO). The high content of elements with low ionization potential should enable a high level of arc discharge stability.

4. 3. Equipment

Thyristor welding power supply UPSH-2500 (Ukraine) with adjustable external I-V characteristic and welding cycle control unit on a programmable microcontroller. Welding gun with pneumatic drive of the working rod and increased length of its working stroke. To record current and voltage oscillograms, a PICO Scope 2206B oscilloscope (Great Britain) and PicoScope 7 software (Great Britain) were used. A significant advantage of this equipment is the built-in mathematical functions that make it possible to automatically calculate the average value of the signal, the standard deviation of this signal, as well as perform mathematical data processing. The scheme of oscillography is shown in Fig. 1.

The dimensions of the weld were measured with a caliper ShTs-1-150 with a measuring range of 150 mm, an accuracy of 0.05 mm, accuracy class I.

To study the process of transferring molten metal, a high-precision laboratory balance Dj-1000-0.01 (China) with a measuring range of 1000 g, an accuracy of 0.01 g, accuracy class II (certificate No. UA.TR.113-0522-20) was used.

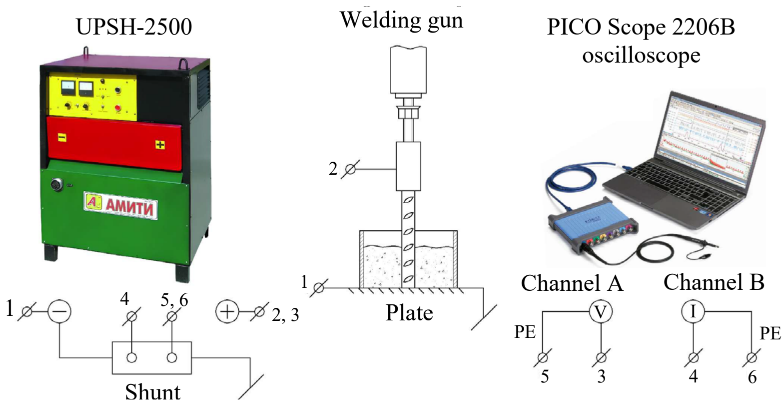


Fig. 1. Connection diagram of equipment and devices when oscillographing arc parameters

4. 4. Methodology and experiment design

The qualitative formation of a weld depends on two parameters: the amount of molten metal (the molten part of the reinforcing bar) and the speed and uniformity of the rod lowering. The stability of the mass of the molten part of the rod transferred to the welding bath depends on the stability of the electric arc process, and the lowering of the rod depends on the design and characteristics of the developed welding gun. The process of forming a weld was studied separately.

Experimental studies were carried out in two stages.

At the first stage, the influence of the welding mode parameters on the stability of the electric arc process and the dimensions of the weld was studied. During the studies, the reduction in the mass and length of the rod, the diameter and height of the layer of deposited metal without forming a welded joint were measured, i.e. the rod was not immersed in the welding bath at the end of the process. At the second stage of the study, based on previously obtained data, the optimization of the welding mode parameters was performed taking into account the stability criteria of the electric arc process and the geometric characteristics of the weld and was tested experimentally by welding 10 control samples.

When planning this experiment, the following mode parameters were selected as factors (independent variables): welding current I and welding time t. The optimization parameters in the experiment were the length of the melted part of the rod L_0 and the dimensions of the deposited bead.

In order to assess the influence of factors on the optimization parameters, three levels of current strength were selected: lower – $I = 1000$ A, zero – $I = 1250$ A and upper – $I = 1500$ A. For each current strength, three levels of welding time were also selected: lower – $t = 2$ s, zero – $t = 3$ s, upper – $t = 4$ s. Thus, taking into account the triple duplication of each experiment, the plan matrix covered 27 experiments. For the analysis, the arithmetic mean value of the indicator obtained from the results of three experiments performed using the same welding mode was used.

5. Results of investigating the technological stability of welding of anchor rods from reinforcing steel by extended arc submerged arc

5. 1. Features in the formation of a weld seam when welding anchor rods by extended arc

To understand the results of our study, it is necessary to consider the welding of a reinforcing rod in stages (Fig. 2) and define technological parameters that are not characteristic of other welding techniques.

Before welding, the operator must set the following technological parameters: welding current I_{weld}, A; welding time t, s; preliminary extension of the reinforcing bar h, mm; height of the reinforcing bar lifting H_l, mm.

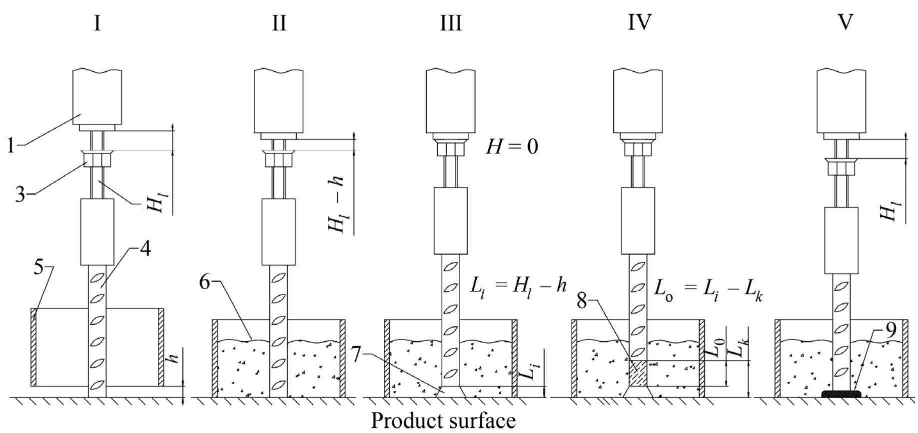


Fig. 2. Stages in the submerged arc welding process of reinforcing bars

At stage I (Fig. 2), the operator, holding the welding gun 1, must set the reinforcing bar 4 to the initial position. The preliminary extension of the bar h is adjusted by changing the position of the flux holder 5 relative to the reinforcing bar. The adjusting nut 3 can be used to adjust the height of the rod lifting H_l. The ratio of these parameters and the length of the melted part of the rod L_0, which depends on the values of I and t, determines the depth of immersion of the reinforcing bar in the welding bath.

At stage II, the operator, pressing the flux holder to the welding plane, must supply welding flux 6 into its cavity.

At stage III, the welding arc 7 is excited, the working rod 2 is raised under the action of a pneumatic cylinder to a distance $H_l - h$.

At stage IV, rod 4 remains stationary, but its part 8 is melted under the action of the welding arc. At the same time, a slag bubble is formed, which reliably protects the welding zone.

At stage V, the rod is lowered to a distance H_l and, immersing in the welding bath, forms a weld seam 9.

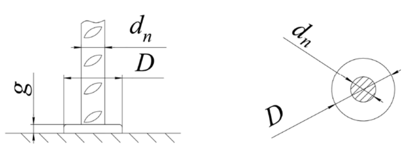
From Fig. 1 it is seen that the optimal setting is one that enables the immersion of the reinforcing rod into the welding bath at the end of the rod lowering (stage V), when its end touches the welding surface. Under these conditions, the functionality for setting the welding mode parameters is written in the form

$$h = L_0 = f(I, t). \quad (1)$$

Physically, this means that the length of the melted part of the rod, which depends on the current and welding time, should be equal to the previous rod protrusion. The rod lifting height H_l should be greater than h by value L_i – the initial arc length, which according to the requirements of EN ISO 14555 is recommended to be set at 3...4 mm. Thus, the rod lifting height should be equal to

$$H_l = h + L_i. \quad (2)$$

The dimensions of the weld are regulated by the requirements from the DSTU B V.2.6-169:2011 standard. In this case, the main controlled parameters are the outer diameter D and the weld height g. The permissible weld diameter, according to Fig. 3, should be within $D = (1.5...2.5)\ d_n$, where d_n is the diameter of the reinforcing bar, height – $g = 3...10\ mm$. The key parameter of the welded connection of the anchor rod is the outer diameter D as it has a greater effect on the shear strength of the connection than the weld height g [16].



a *b*

Fig. 3. Controlled dimensions of the weld:
a — side view; *b* — top view

Since the only source of metal for forming the weld is the molten part of the reinforcing bar, the required length L_0 is determined from the following considerations.

The molten part of the reinforcing bar is completely immersed in the welding bath. To form a weld (in the form of a ring) with the dimensions recommended by the DSTU B V.2.6-169:2011 standard, an additional volume of molten metal is required from a portion of the rod – a cylinder with a diameter d_n and a length L_0. This additional volume forms a ring with an outer diameter D, an inner diameter d_n, and a height of g. Then

$$\frac{\pi g}{4}\left(D^2 - d_n^2\right) = \frac{\pi d_n^2}{4} L_0. \quad (3)$$

Hence

$$L_0 = \frac{\left(D^2 - d_n^2\right) g}{d_n^2} = \left[\left(\frac{D}{d_n}\right)^2 - 1\right] g. \quad (4)$$

The difficulty in determining the required value of L_0 is the impossibility of specifying the values of D and g in advance, as is done when welding with a ceramic ring, the dimensions of the internal cavity of which determine the specified parameters. When welding under flux, the shape of the seam becomes more natural, but its dimensions depend on the viscosity, the temperature interval of crystallization of the molten flux, and other technological properties of the slag [15].

Taking into account the free formation of the seam under flux, and therefore the possibility of spreading the liquid metal along the plane, the seam diameter should be close to the maximum value $D = 28$ mm, and the seam height – to the minimum $g = 4$ mm. The calculated mass of the deposited metal can be determined from the well-known formula

$$M = \alpha_d I t, \quad (5)$$

where $\alpha_d = 12 \cdot 10^{-3}$ – deposition rate, kg/A·h [17].

According to the assumptions and geometric condition of equation (4), the molten length of the rod should be $L_0 = 8$ mm, which corresponds to the mass $M = 12$ g of molten metal. The preliminary rod protrusion is $h = 8$ mm, the rod lifting height $H_l = 12$ mm.

According to the research program, measurements of the dimensions and mass of the molten rod and the plate with the deposited roller were performed under different modes (Fig. 4).

a

b

c

Fig. 4. General view of the melted rod and the deposited roller at different mode parameters: *a* — $I = 1250$ A, $t = 3$ s; *b* — $I = 1250$ A, $t = 3$ s; *c* = $I = 1500$ A, $t = 4$ s

The averaged results of measurements and weighing of three samples melted under the same mode in each experiment are given in Tables 2, 3, respectively.

Table 2

Reduction of mass ΔM and rod length ΔL depending on welding mode

Welding mode	Indicator					
I, A	1000		1250		1500	
t, s	ΔM	ΔL	ΔM	ΔL	ΔM	ΔL
2	6.10	3.33	7.79	4.33	11.10	8.00
3	9.55	5.67	12.63	7.67	17.94	12.00
4	12.52	7.33	16.19	12.00	21.95	14.67

Analysis of our data confirms the following regularities:

– an increase in the mass of the molten metal of the anchor rod leads to a change in the dimensions of the deposited bead;

– an increase in the current strength and welding time causes an increase in the diameter D and height g of the deposited bead;

– the ratio D/g changes little with a change in the welding time but increases with an increase in the current.

Table 3

Geometric parameters (diameter D and height g), mm of the deposited bead depending on the welding mode

Welding mode	Indicator					
I, A	1000		1250		1500	
t, s	*D*	*g*	*D*	*g*	*D*	*g*
2	23.30	3.60	26.49	3.53	31.01	3.87
3	26.92	4.35	29.86	4.50	35.71	4.40
4	28.01	4.50	33.31	4.73	37.81	4.50

5. 2. Research on destabilizing factors of the electric arc process

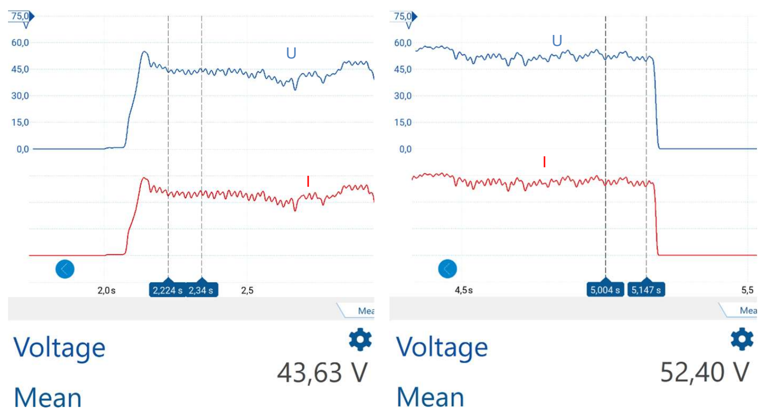
In order to quantitatively assess the technological stability of the electric arc process, the oscillograms of the current and arc voltage with automatically determined average values and standard deviations of the studied parameters were recorded and analyzed (Fig. 5).

The obtained oscillograms and the mathematical apparatus built into PicoScope 7 provide the opportunity for a deep analysis of the electric arc process. Let us analyze the sections of the specified current and voltage oscillograms at the beginning (Fig. 6, *a*) and at the end (Fig. 6, *b*) of the welding process under the welding mode $I = 1250$ A, $t = 3$ s. The voltage oscillograms confirm the peculiarity of the electric arc process – a gradual increase in the arc voltage (by 9 V) due to its elongation during the melting of part of the reinforcing bar.

Thus, the technological increase in the arc length is the main factor of instability for both the welding arc and the welding process as a whole.

Another negative factor that can significantly affect the stability of welding is the initial stage of excitation of the welding arc, when it undergoes the greatest fluctuations. Without ensuring stable excitation of the arc (Fig. 1, stage III), the stability of the process of welding a ribbed reinforcing bar with a submerged arc is not possible. The equipment of the soviet production was based on power sources that did not have devices for exciting the arc. In this study, specially designed equipment with an auxiliary power source with an operating voltage of up to 60 V was used to ignite the excitation arc with a current of up to 10 A. The technical solution found has made it possible to execute a welding process with stable arc excitation.

The algorithm of operation developed for such a combined power source enables arc excitation without unwanted sticking of the reinforcing bar at the moment of its contact with the surface of the article due to a short circuit at the beginning of welding.



a *b*

Fig. 6. Change in voltage U and arc current I during welding: *a* – at the beginning of welding (Fig. 2, stage III); *b* – at the end of welding (Fig. 2, stage IV)

Fig. 5. Characteristic oscillograms of current I and voltage U of the electric arc welding process of a reinforcing bar

The process of arc excitation, as well as parameters that enter a stable welding mode, are illustrated by the voltage and current oscillograms (Fig. 7).

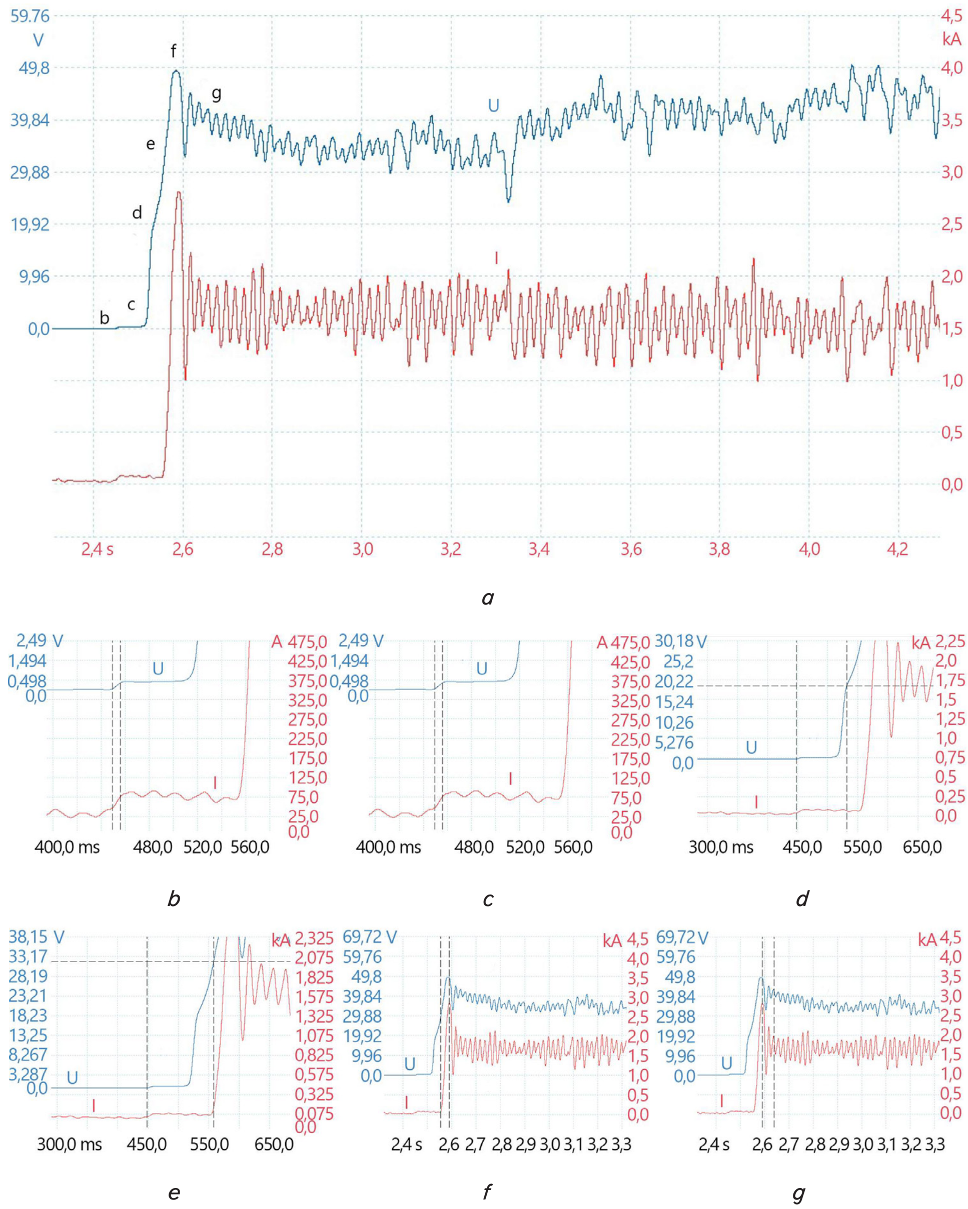


Fig. 7. Oscillograms: *a* – start of the cycle and achieving of stable parameters under the general welding cycle mode; *b* – program start; *c* – contact establishment; *d* – excitation arc initiation; *e* – switching on the main source; *f* – switching on the stabilization system; *g* – welding current stabilization

At the initial stage of the welding cycle (Fig. 7, *a*) 6 characteristic stages with corresponding parameters can be distinguished:

1) Fig. 7, *b* – pressing the "Start" button; switching on the auxiliary source. Short-circuit voltage $U = 0.55$ V, stage duration $t = 6$ ms;

2) Fig. 7, *c* – determining the contact between the reinforcing bar and the plate. Voltage $U = 0.55...0.80$ V. In the absence of contact, the voltage corresponds to the no-load voltage of the auxiliary source – not less than $U = 70$ V. The signal "voltage less than 5 V" is evidence of the presence of contact. The control system is triggered; the pneumatic cylinder of the gun raises the reinforcing bar. The total duration of the stage $t = 72$ ms;

3) Fig. 7, *d* – initiation of the excitation arc. The separation and lifting of the reinforcing bar leads to the extension of the arc, the system controls the voltage and the presence of current in it. The duration of the stage t = 23.6 ms;

4) Fig. 7, *e* – switching on the main source when reaching the preset value $U = 32$ V and the presence of the excitation arc current, the welding power source is switched on automatically. The duration of the stage $t = 23.5$ ms. The countdown of the welding time begins directly;

5) Fig. 7, *f* – increase in welding current, start of operation of the welding current stabilization system. Duration of stage $t = 24.9$ ms;

6) Fig. 7, *g* – stabilization of welding current to a predetermined value. Duration of stage $t = 28.64$ ms.

The boundary of stages 2 and 3 is conditionally determined by the voltage of the auxiliary source $U = 20$ V, as sufficient to create an excitation arc. Control of the current and voltage of the excitation arc in stages 2 and 3 is important because, if the voltage does not increase, or the current is absent, this means that the excitation arc is either not excited or extinguished. In this case, the control system stops the process without turning on the main welding power source to prevent damage to the end of the rod. The total time from pressing the "Start" button to turning on the welding power source (stages 1...4) is $t = 125.1$ ms.

Technological increase in the arc, on the one hand, is a destabilizing factor, and on the other hand, it is an inherent specificity of the extended arc welding method. Given the number of different technological parameters of the welding mode, their selection empirically is a difficult task and does not guarantee a positive result.

5. 3. Quantitative assessment of the technological stability of the electric arc process

From the study of the oscillogram (Fig. 5), it can be concluded that the nature of the welding process of the reinforcing bar corresponds to the classical submerged arc welding process – without short circuits of the arc gap. In this case, the coefficient of variation K_V was adopted as the criterion for assessing the stability of the process – the percentage ratio of the root-mean-square deviations to the average value.

In this case, we relied on the results reported in [18], which showed that if the values of the coefficients of variation of current K_V^I and voltage K_V^U are less than 33%, the electric arc process can be considered stable.

In [19], more stringent limits are proposed for determining stability: $K_V^I, K_V^U < 20\%$. The coefficients of variation of current K_V^I and voltage K_V^U calculated and averaged according to the results of three experiments (Table 4) indicate high stability of the process over the entire studied range of mode parameters.

Table 4

Average coefficients of variation in arc current K_V^I and voltage K_V^I, %, depending on the welding mode

Welding mode	Coefficients of variation					
I, A	1000		1250		1500	
t, s	K_V^I	K_V^U	K_V^I	K_V^U	K_V^I	K_V^U
2	12.83	11.40	7.91	9.76	13.16	10.55
3	13.23	13.69	9.19	10.44	13.31	11.36
4	16.49	14.69	12.87	13.69	13.61	13.39

From Table 4 it can be seen that the optimal parameters of the welding mode, from the point of view of the stability of the electric arc process, are: $I_{weld} = 1250$ A, $t = 2$ s.

5. 4. Engineering methodology for determining the optimal parameters of the welding mode of anchor rods

The parameters of the welding mode of an anchor rod made of reinforcing steel are considered optimal provided that the technological stability of the arc welding process is ensured.

To define the optimal parameters of the welding mode, an engineering methodology has been devised, the use of which can be demonstrated using a nomogram in Fig. 8.

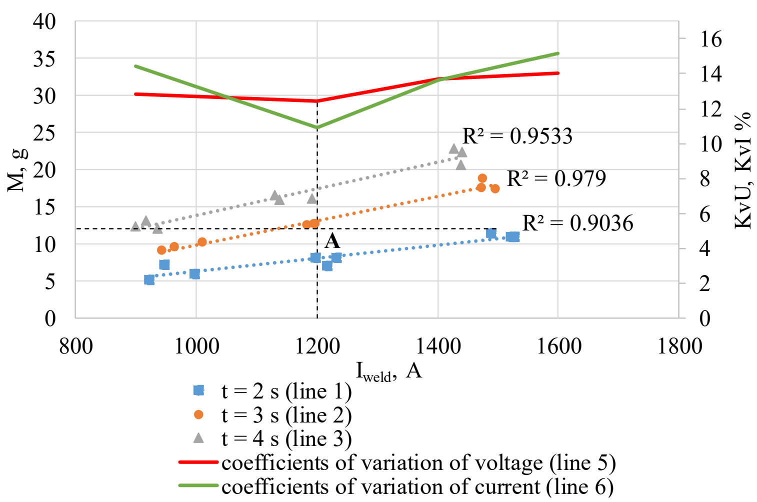


Fig. 8. Nomogram for determining optimal welding mode parameters

The abscissa axis shows the welding current, the left ordinate axis shows the mass of the deposited weld metal, and the right axis shows the values of the current and voltage variation coefficients.

Linear plots 1–3 (Fig. 8) illustrate the dependence of the mass of the molten metal on the welding current and welding time ($M = f(I, t)$), the horizontal dotted line 4 corresponds to the mass of the deposited metal $M = 12$ g, calculated above.

In the upper part of the nomogram, there are broken lines 5 and 6, which characterize the change in the coefficients of variation of voltage K_V^U and current K_V^I, respectively.

In Fig. 8, the vertical dotted line 7, which intersects plots 5 and 6 at the point of their minimum, corresponds to the welding current strength, which provides the greatest stability of the arc process. Point A, the intersection of dashed lines 4 and 7 (Fig. 8), determines the optimal mass of deposited metal for the formation of the weld seam under the most stable mode of the electric arc process.

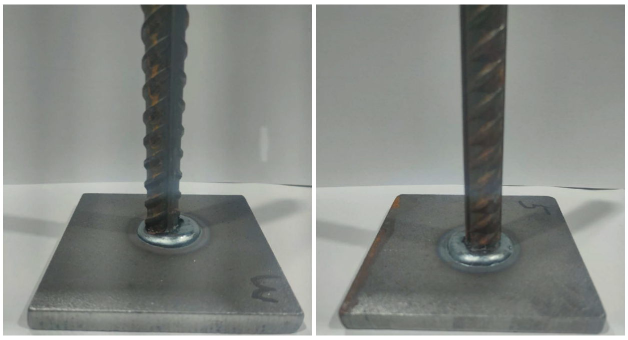
The procedure for finding the optimal parameters of the mode using the nomogram involves the sequential execution of the following actions. First, the range of welding current is set, in which the electric arc process is most stable. Second, the welding time is determined, which provides the required volume of molten metal for the formation of a weld seam with predetermined geometric dimensions. Using the volume of molten metal and dependences (1) to (5), it is possible to determine the preliminary departure and the height of the anchor rod lift. As an example, using the devised methodology, the optimal parameters of the mode for welding a ribbed reinforcing bar with a diameter of 16 mm were established, namely: welding current $I = 1200$ A; welding time $t = 3$ s. In this case, the preliminary extension of the anchor rod is $h = 8$ mm; the rod lifting height $H_l = 12$ mm.

The resulting optimal parameters of the welding mode were used in the second stage of research for welding a batch of control samples in the amount of 10 pcs. The general appearance of the welded joints made under the optimal mode is satisfactory (Fig. 9).

Measurements showed that the weld dimensions are $D = 32.5 \pm 1.5$ mm, $g = 3.9 \pm 0.35$ mm, which meets the requirements from the DSTU B V.2.6-169:2011 standard. At the same time, a small deviation in the weld dimensions from the average value ($D < 5\%$, $g < 9\%$) confirms not only the high stability of the obtained electric arc discharge but also the entire process of forming the weld in general.

At the same time, the experience of welding more than 50 samples showed that with standard preparation of the plate surface and the use of rods after mechanical cutting, a failure of the arc excitation process was observed only once. Thus, it is proven that the applied automatic welding control system enables the reliability of the welding arc excitation and reaching the optimal parameters of the mode, i.e., ensures the technological stability of the welding process.

In general, the result of our research is the development of an industrial technology for submerged arc welding of reinforcing steel anchor rods. But here it should be noted that the EN ISO 14555 standard, in addition to the dimensions of the seams, establishes requirements for the tensile strength of the joint. For a comprehensive verification of the devised technology for welding reinforcing rods for compliance with all the requirements of the specified standard, the program of subsequent research involves a set of metallographic studies and mechanical tests of welded joints.



a *b*

Fig. 9. Samples welded under the optimal mode: *a* – sample No. 3; *b* – sample No. 5 (Table 5)

6. Discussion of results based on investigating the influence of mode parameters on the stability of the process of welding reinforcing bars with an extended arc

In papers [7–11] that consider the technique of welding rods with an extended arc, the results of studies on the standard welding technique using a typical range of anchor rods are reported. The welding modes corresponded to the range of the standard technological process: $I_{weld} < 600$ A, $t_{weld} < 1$ s. In our work, a study of the technological stability of welding reinforcing bars under flux with free formation of the seam at currents over 1200 A was conducted.

A step-by-step analysis of the welding process of reinforcing bars (Fig. 2) reveals that most of the molten metal required for forming the weld occurs as a result of the melting of the rod itself. By changing the parameters of the welding mode, it is possible to control the melting of the rod and, as a result, the formation of the weld.

Analysis of the data in Table 2 also confirms the well-known regularity (5) – the mass of the molten electrode metal increases in proportion to the increase in the current strength and welding time. Calculations have shown and experimentally confirmed that in the process of welding the anchor rod, the length of its molten part and, accordingly, its mass increases (Table 2, Fig. 4). For example, the mass of the metal of the molten part of the rod calculated for the welding mode $I = 1250$ A, $t = 3$ s is $M = 12$ g, and determined as a result of the experiment with the same welding parameters $M = 12.63$ g, i.e., the error does not exceed 5%.

A similar regularity is also characteristic of the dimensions of the deposited bead (Table 3). The increase in the current strength and welding time causes an increase in the diameter D and height g of the deposited bead. It should be noted that the D/g ratio changes little with the change in welding time but increases with increasing current on average from 6.3 (at 1000 A) to 8.2 (at 1500 A). This indicator clearly demonstrates that the spreading of liquid metal during free formation of the weld depends more on the current strength than on the heating time.

It should be noted that a sharp increase in the arc length due to the lifting of the rod and its melting causes an increase in the arc voltage (Fig. 5, 6) and is the main destabilizing factor. The following techniques for increasing welding stability are proposed: technical – through the operation of welding equipment; technological – the use of flux with components with low ionization potential.

At the initial stage, the power source must provide two conditions necessary for entering a stable welding mode. First, to create a conductive channel for guaranteed arc excitation and rapid current growth. Second, to stop the sharp increase in current as soon as possible when it reaches a given level. The algorithm of operation of such a source is demonstrated in Fig. 7.

The influence of welding flux components on the stability of the burning of a drawn arc has already been studied previously. Thus, using high-speed video recording and destructive static tensile tests, the positive influence of the Al_2O_3 component on the stability of the arc process has been shown [11].

By oscillography of the energy parameters of the welding arc and assessment of their deviation from the average value, it was found [15] that the introduction of SiO_2 and TiO_2 components into the flux also has a positive effect on the stabilization of the arc discharge.

The results of our work fully confirm conclusions from previous studies. The use of welding flux containing Al_2O_3, SiO_2 and TiO_2 enables stable burning of the welding arc in the entire range of welding modes studied (Table 4).

The classic technique of welding using a ceramic ring limits the dimensions of the seam to the dimensions of the inner surface of the ring, so disposable ceramic rings must be used for each diameter of the anchor. The process of free formation of the seam during submerged arc welding of reinforcing bars makes it possible to change the diameter D and height g of the seam, affecting the shear resistance of the entire reinforced concrete joint [16].

The algorithm for calculating the geometric dimensions of the seam depending on the parameters of the welding mode that we developed makes it possible to determine the specified dimensions even before the start of the welding process. The devised methodology for defining the optimal parameters of the welding mode of reinforcing steel bars (Fig. 8) is original and could be used for other anchor nomenclature.

To limit the number of variable parameters, one type of welding flux, aluminate-basic, was used in this study. To expand the scope of use of the technology for welding reinforcing bars in the future, it is necessary to investigate the influence of fluxes of other types on the stability of the arc process and the formation of the weld.

Another limitation of the work is the lack of research on the influence of mode parameters on the mechanical strength of welded joints. For a comprehensive verification of the devised methodology for compliance with all the requirements of EN ISO 14555, the program of subsequent research involves a set of metallographic studies and mechanical tests of welded joints.

The issue of finding an analytical dependence that describes the influence of mode parameters on the quality of the welded joint also remains unresolved. Overcoming this problem requires further expansion of the range of welding modes studied for reinforcing bars of different diameters. Analysis of the obtained data set using methods of mathematical statistics, similarly to [7, 10], will make it possible to reveal the dependence between the change in mode parameters and the final result of the welding process.

The use of such dependences could improve the feasibility of using the technology of submerged arc welding of reinforcing bars.

7. Conclusions

1. For welding of reinforcing steel anchor rods with a submerged arc, the required length of the melted part of the rod L_o was calculated to obtain a weld with dimensions regulated by DSTU B V.2.6-169:2011. It was found that the weld diameter D and its height g increase in proportion to the increase in the welding current and welding time. The ratio D/g practically does not change with the change in welding time but increases with the increase in the current.

2. It was found that the destabilizing factors of the electric arc process are the change in the voltage and current of the welding arc and its technological elongation during welding. Reliable arc excitation, automatic access to optimal welding mode parameters, and maintaining high stability of the electric arc process are provided by an auxiliary low-current power source and a designed control system for the welding technological complex.

3. To quantitatively assess the stability of the electric arc process when welding anchor rods made of reinforcing steel, the coefficients of variation of current K_V^I and voltage K_V^U. can be used. In the studied range of welding modes, the calculated indicators are $K_V^I = (16.49...7.91)\%$ and $K_V^U = (14.69...9.76)\%$, respectively, which are less than the critical value $K_V = 20\%$, which indicates high stability of the process.

4. An original computational and experimental engineering methodology has been devised to determine optimal parameters for the welding mode for anchor rods made of reinforcing steel. For welding a ribbed reinforcing rod with a diameter of 16 mm, the determined optimal parameters are: welding current $I = 1200$ A; welding time $t = 3$ s. In this case, the preliminary protrusion of the anchor rod is $h = 8$ mm; the rod lifting height $H_l = 12$ mm. Experimental verification of the defined welding mode parameters has proven that the dimensions of the welds comply with the requirements from the DSTU B V.2.6-169:2011 standard.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Yuriy Yaros: Conceptualization, Methodology, Writing – original draft; **Dmytro Hladchenko**: Investigation, Resources; **Stanislav Drahan**: Project administration, Writing – review & editing.

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