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Study on pulsed-arc welding issues at the Machines and Welding Production Automation Department, RIAE — DSTU

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Introduction. The history of solving the problem of welding structures made of stainless and heat-resistant metals and alloys goes back several decades. Researchers were particularly interested in working with deformed aluminum alloys 2–6 mm thick. As a rule, such thin-walled structures are welded in an argon shielding gas at relatively small currents; therefore, metal transfer is large-droplet (the weld is shaped in the form of separate large droplets with a narrow penetration of the welding components). At the same time, the weld is very convex, which does not meet the operational requirements of the structures. Thus, it was important to solve the following problems: to obtain a controlled fine-drop transfer of electrode metal at currents corresponding to a large-drop transfer; to determine a condition for the controlled transfer; to develop a power supply system for the welding arc.

Materials and Methods. The behavior and parameters of the arc were recorded through the high-speed film and video shooting with synchronous oscillography of the electrical process parameters – current and voltage. They were recorded by light-beam oscilloscopes and two-screen oscilloscopes. The data were processed using a computer complex and *Diadem* 10.1 software.

Results. The basic condition for the controlled metal transfer is determined through applying current pulses to the welding arc from special pulse sources with and without energy storage devices. Transients in the electrical circuits of the main welding source during the current pulse action and pause are considered. The factors providing stability of rigid and flexible pulsed-arc welding (PAW) are indicated.

Discussion and Conclusions. The results of studying the possibility to control the welding arc processing behavior and the proposed methods for calculating the parameters of the PAW mode became the basis for the development of technology and equipment for the mechanized GMAWP of aluminum alloy assemblies. They are introduced at the enterprises of the aviation industry, shipbuilding. Solutions for stainless and heat-resistant steels and alloys are used at the motor industry enterprises. As a result of studies on the mechanized CO_2 activated electrode wire welding, a mechanized PAW technology was developed for units of stainless steel electric furnace bodies, structures of road-building, agricultural machinery and ships.

Keywords: welding in shielding gases, consumable electrode, current pulse parameters, controlled metal transfer.

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Introduction. Since early sixties of the XX century, gas-shielded consumable-electrode welding of metal structures has been studied [1]. One of the basic problems of this process is the manufacture of welded structures from stainless and heat-resistant metals and alloys. Of particular difficulty was the creation of deformed aluminum alloys 2–6 mm thick. These materials are used in aviation, motor and shipbuilding, in light, food, and chemical industries. Welding of thin-walled structures of these metals was performed, as a rule, by a non-consumable electrode in the argon shielding gas medium with relatively low process productivity. Mechanized consumable-electrode welding at relatively small currents was also used, which means with large-drop metal transfer. In this case, the weld at small currents is formed in the form of separate fused large droplets with a narrow, small penetration of the welded elements, which does not always meet the technical requirements for the structure design.

It is known that there is a critical current under welding in argon. In a narrow range of its changes, the character of metal transfer sharply changes. At currents below the critical level, the metal transfer is globular, and above the critical one, it is spray transfer. In case of the globular metal transfer, a weld of improper shape is obtained – with a narrow, shallow penetration and a large convexity. If the current is higher than critical, during spray transfer, the weld has finger-shaped penetration, which reduces the durability of the weld joint.

During the mechanized welding of a melting electrode wire, the current value periodically changed for a short time. The purpose of this operation is to obtain controlled fine-droplet transfer of electrode metal at currents corresponding to globular metal transfer. In this case, the geometric shape of the weld should meet the technical requirements for welded structures.

Materials and Methods

The arc power system for pulsed arc welding (PAW). To achieve this goal, an arc power system from two electric energy sources has been developed. The system includes:

- the normal power supply is the PSG-500 welding transducer with a flat-dipping volt-ampere characteristic (VAC) since at that time there were no welding rectifiers for the mechanized welding in shielding gases;

- a special switching power supply (SPS) is a pulse energy storage generator.

The normal and pulsed sources were connected in parallel to the arc gap.

In the first arc SPS developed, 150 A current ignitrons were used as power controlled rectifiers. Then, when the VK-200 and VT-150 power semiconductor rectifiers became available, they began to manufacture and introduce switching power supplies for semiconductor valves at enterprises. Switched energy storage power supplies are protected by copyright[1, 2].

When the normal and SPS of the arc are connected in parallel [2], an increased voltage is applied to the arc under the current pulse pile-up. It is directed opposite to the normal source and "locks" it due to the presence of an uncontrolled rectifier *V*2 in its circuit (Fig. 1). A decrease in current in the normal source circuit under the action of a current pulse is meant by "locking".

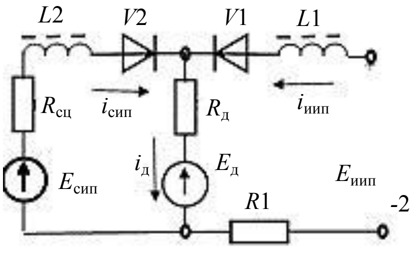


Fig. 1. Equivalent circuit of arc supply from normal and switched power sources: $E_{сип}$, $E_{иип}$, $E_{д}$ are voltage of welding, switched power sources and arc; $i_{сип}$, $i_{иип}$, $i_{д}$ are current of welding, pulsed sources and arc; $R_{сц}$, $R1$, $R_{д}$ are active resistance of the welding circuit, pulse source and arc; $L2$, $L1$ are inductance of the circuit of the welding and pulse sources; $V2$, $V1$ are rectifiers in the circuit of the welding and pulse sources

However, despite the presence of the *V*2 rectifier, the "locking" of the normal source does not occur instantly. Due to the inductive resistance *L*2, a transient process occurs in the circuit (during the pulse pile-up and after its action).

Consider the transition process of current variation in the normal source circuit when a current pulse is applied. To do this, we solve a linear differential equation compiled for the normal power supply circuit (see Fig. 1):

[1] Budnik NM, Dyurgerov NG, Sagirov KhN, et al. *Ustroistvo dlya impul'sno-dugovoi svarki*: *A.S. 226752 SSSR* [Device for pulsed-arc welding: author's cert. no. 226752] USSR, 1968.

[2] Budnik NM, Sagirov KhN, Dyurgerov NG, et al. *Ustroistvo dlya impul'sno-dugovoi svarki: A.S. 299111 SSSR* [Device for pulsed-arc welding: author's cert. no. 226752] USSR, 1971.

$$E_c = L_2 \frac{dI_б}{dt} + R_2 I_б + R_д i_{иип}. \quad (1)$$

Here, $E_с = E_{сип} - E_д$, $R_2 = R_д + R_{сц}$; $I_б$ is current of the normal power source; $i_{иип}$ is free current in the pulse (for example, for sinusoidal pulses with a damping amplitude):

$$i_{иип} = \frac{E_{иип} - E_д}{\omega_0 L1} exp\left(-\frac{R_{иц}}{2L1} t\right) sin\omega_0 t,$$

where $R_{иц} = R_1 + R_д$, $\omega_0 = \sqrt{\frac{1}{L1C} - \frac{R_{иц}^2}{4L1^2}}$.

After the pulse end, the current in the normal source circuit increases exponentially, it is determined by the time constant of the normal power source circuit $\tau_{сц} = R_{сц}/L_2$.

$$I_б\,(t)_{t_и \to T_ц} = \left[I_{д0} - I_б\,(t)_{t=t_б}\right]\left(1 - exp - \frac{t}{\tau_{сц}}\right) + I_б\,(t)_{t=t_б}. \quad (2)$$

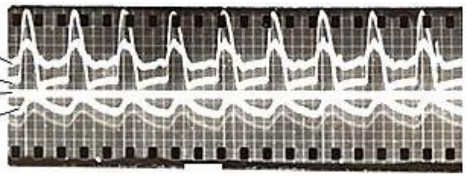
Based on the equations (1 and 2), the law of the current variation in the circuit of the normal source was obtained during the current pulse pile-up and after its end [3, 4].

Research methodology. The arc behavior and its parameters under welding at various spatial positions of non-ferrous and ferrous metal samples were recorded by high-speed film shooting up to 5000 frames/s and video shooting 2000 frames/s. At the same time, synchronous oscillographic testing of the process electrical parameters was performed: the arc current and voltage were recorded by the light-beam and electronic oscilloscopes. The data obtained by means of a two-screen electronic oscilloscope was processed using a computer complex and *Diadem* 10.1 software.

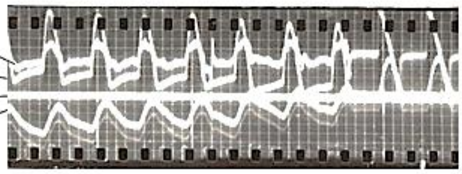
We studied the nature of metal transfer, the weld formation, and determined the PAW physical and process parameters in the protective gases of these metals.

Research Results

Welding in argon protective environment. An analysis of the obtained patterns provides evaluating of the effect of the PAW mode parameters on the joint operation of the arc feeding system, in which the welding process becomes unstable. Oscillograms of the PAW process at various inductances of the welding power supply circuits are shown in Fig. 2.



a)

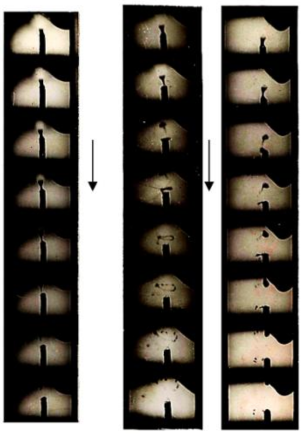


b)

Fig. 2. Oscillogram of current ($I_д$), voltage ($U_д$) of the arc and current in the circuit of the welding power source ($I_{сц}$) ($t_и = 4.6 \cdot 10^{-3}$s, $I_и = 690$ A, $f = 100$ cps): continuous arcing $I_{ср} = 70$ A, $L = (1.0 \div 1.1) \cdot 10^{-3}$ H (*a*); intermittent arc burning $I_{ср} = 150$ A, $L = 0.3 \cdot 10^{-3}$ H (*b*)

The natural (non-pulsed) and pulsed welding processes are considered. It is established that for identical values of the effective current, the velocity of droplet movement in the arc gap is always higher under PAW. Moreover, a larger current in the pulse at the moment of its detachment from the electrode always corresponds to a larger drop velocity. Separation of the droplet from the electrode can occur in various phases. It depends on the welding mode and current pulse parameters.

When the droplet is detached at the end of the pulses, the current is close to the base current of the welding process, and the droplet flying speed reaches 1.2–2.0 m/s. In this case, a controlled directional metal transfer is provided under welding in all spatial positions with minimal metal loss through splatter (Fig. 3 *a*).



a) *b*)

Fig. 3. PAW records of aluminum alloy AMg6 in the overhead position under various modes (shooting speed is 4000 frames/s, welding wire is AMg61 1.6 mm in diameter): effective current is $I_{эф}$= 100 A, $t_и = 2.5\cdot10^{-3}$ s, $I_и$ = 310 A, f = 50 cps (*a*); $I_{эф}$ = 180 A, $t_и = 4.5\cdot10^{-3}$ s, $I_и$ = 500 A, f = 50 cps (*b*)

It is established that the minimum amplitude of the current pulse $I_{\text{п}\,min}$, which provides a transition from uncontrolled transfer to controlled transfer, depends on:

— surface tension of the electrode metal $\sigma_п$,

— electrode diameter $d_э$,

— welding mode parameters, $I_{эф}$, $v_п$:

$$I^2_{\text{п}\,min} t_и = A_1 \sigma_п d_э^2 f^{0,5}/I_с. \quad (3)$$

In the case of droplet detachment from the electrode at an amplitude value of the pulse current, its flying speed in the arc gap can exceed 8 m/s. This causes the appearance of:

— near-weld splashes (due to spattering of molten metal from the weld pool),

— a weld-affected zone of fine droplet spraying formed when a neck of a molted metal breaks between an electrode and a droplet (see Fig.3 *b*).

To reduce the metal loss due to spatter, the amplitude of the current pulse should not exceed 1.1 $I_{\text{п}\,min}$.

The increase in $I_п$ is limited by the condition of continuous arc burning: if the effective current is constant, then with an increase in the amplitude, frequency, and pulsewidth, the base current decreases.

When the base current decreases below the minimum steady-state current of the arc, its breaks occur (the welding current is interrupted), the stability of the welding process is violated (see Fig. 2 *b*). This condition was used to determine the maximum values of the pulse parameters. For example, the maximum amplitude of a pulse from a source with energy storage for unipolar current pulses (damped sinusoid):

$$I_{пmax} < \frac{2I_C}{\pi t_ц f^{0,5}} \sqrt{(\pi^2 t_ц^2 + t_и)} \Big/ \sqrt{t_ц\left(1 - exp\left(\frac{2t_и}{RC}\right)\right)}. \quad (4)$$

Fig. 4 shows the dependences of the minimum required amplitude of the pulse current (curves 1, 1') and the maximum allowable amplitude (curves 2, 2') on their repetition rate for different pulsewidth. Curves 1, 1' (with increasing current) are the boundary of the transition from uncontrolled transfer of metal droplets to the controlled transfer. Curves 2, 2'are the boundary of the transition from controlled droplet transfer to arc burning cessation. These curves limit the range of the PAW modes by a consumable electrode.

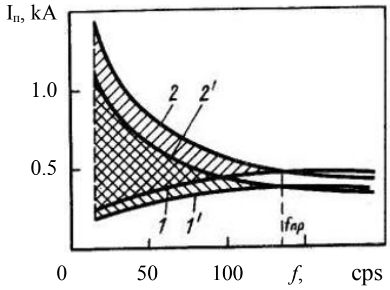


Fig. 4. Areas of permissible amplitude values of current pulses: argon, alloy AMg6, $I_{эф}$ = 140 A; 1, 2 — $t_и$ = 1.4 ms; 1', 2' — $t_и$ = 2.2 ms

From the equations (3) and (4), it follows that with an increase in the pulse repetition rate, the minimum required amplitude of the current increases, and the maximum allowable amplitude decreases. The area of controlled drop transfer narrows.

Under the limiting current pulse rate ($f_{пр}$), the frequency is adopted at which the minimum required amplitude of the current pulse is the maximum allowed. This frequency was determined through solving equations describing $I_{п\,min}$ (3) and $I_{пmax}$ (4).

Welding in active shielding gases. Welding in active shielding gases (CO_2, N_2 and mixtures of Ar < 80 % + CO_2 > 20 %) and He on the current of direct and reverse polarity is considered. It was established that in this case, the current pulse pile-up with the parameters used for welding in argon does not provide the controlled metal transfer [4, 5]. The current pulse pile-up under the activated electrode wire welding (alkali salts) by the current of direct polarity provides stabilization of the arc – it takes the shape corresponding to the current higher than critical. However, in the pulse spacing, when the arc current is less than critical, it wanders intensively. If a drop passes from the electrode at the end of the pulse, when the current decreases to below a critical value, then the detachment and transfer of the drop takes place in an erratic arc. In the pulse spacing, the electrode wire melts, and at its end, there is always a certain amount of molten metal. Due to the wandering of the arc, the drop moves relative to the axis of the electrode wire. When a pulse pile-up, the drop detaches and may not fall into the weld pool. The pulse pile-up with duration of 1.2–1.8 ms causes the detachment of droplets from the electrode wire with each current pulse; however, it does not provide directional transfer of metal into the weld pool and is characterized by increased spatter.

It was found that non-coaxial droplets, under current pulse pile-up, deviate to a greater extent from the electrode wire axis than coaxial ones. The largest number of misaligned droplets detaches from the electrode at an angle of 20–30° and does not fall into the weld pool. Coaxial drops detach at an angle not exceeding 10°.

When the pulsewidth is 4.0–5.0 ms, the base current of the welding process decreases due to the integral self-regulation of electrode melting [6, 7]. At the end of the electrode wire, despite the wandering of the arc during cessation, a small volume of molten metal is formed. As a rule, under the current pulse action, several coaxial droplets are formed, which are transferred to the weld pool, and this causes small spatter.

To reduce the metal loss due to spatter under the activated electrode welding in active shielding gases and their mixtures, it is required to combine the processes of melting and droplet transfer into the weld pool. The electrode wire should melt at a current above critical, when the arc is spatially stable and does not cause deviation of the flight trajectory of droplets from the electrode axis in the interelectrode gap [8, 9]. This is achieved as follows: current pulses of the same polarity are superimposed on a continuously burning arc with the minimum possible amplitude $I_п$ = (1.5–2.0) $I_{кр}$ and the maximum possible duration $t_и$ = 4.0–10 ms at a pulse repetition rate of 100– 50 cps. The base current is selected to be minimal (so that during cessation, the electrode wire does not practically melt). In this case, during the period of the pulse action, short-term spray transfer (ST), called intermittent spray transfer (IST), occurs. When the pulse amplitude decreases below 1.5 $I_{кр}$, metal spray transfer is impossible.

A nonstorage switched power supply has been developed and manufactured for the practical implementation of the described process.

For the first time, the features of the weld formation under PAW were determined. The nature of the molten metal displacement in the weld pool was studied with and without current pulse pile-up on the arc. This provided determining factors that improve the weld formation and the retention of the metal of the weld pool under PAW in various spatial positions.

Using high-speed filming (up to 5000 frames per second), it was found that under PAW, molten metal is displaced from the head end of the weld pool under the action of arc pressure and pressure created by drops of a transferred electrode metal [3]. It turned out that the speeds of molten metal movement caused by the arc pressure under the action of the current pulse and the kinetic energy of the droplets were commensurate. Therefore, in case of PAW, in one cycle, the molten metal is twice displaced from the head end of the pool to its tail end.

The move frequency of molten metal in the pool increases with an increase in the pulse frequency, ceteris paribus (constant welding current and arc voltage). This cuts cycle time and reduces the amount of transported metal, which crystallizes in a thinner layer, which helps to improve the primary crystallization of the weld metal.

PAW when feeding an arc from two sources (see Fig. 1), as a rule, is performed according to a rigid program with a fixed pulse repetition rate. The shape of the current pulses is similar to the curve of the applied increased voltage (see Fig. 2).

Since 1989, research has been carried out to create welding rectifiers with inverter converters for various with consumable and non-consumable electrode welding methods[1,2].

PAW by pulses of a rectangular shape. Welding rectifiers with an inverter converter are created on the basis of high-frequency inverters with a current conversion frequency of 16 kHz. In this case, power sources of the welding arc are low-inertia — high-speed ones. This provides a curve of the welding current of various shapes with a change in magnitude over a wide range. The rectifiers with combined volt-ampere static characteristics with three prominent sections are most used when performing welding operations. The steep-dipping section at currents less than 30A provides reliable arc striking and the establishment of the welding process. The flat-dipping section and the bayonet section in the range of operating modes provide stabilization of the welding current in a wide range of its regulation, in a wide range of changes in the voltage drop across the arc.

The digital control system for the arc power source provides a fast shape change of the welding current curve and maintaining the bayonet section of the volt-ampere characteristics in the range of the current control limit. The source is equipped with a control system for the consumable and non-consumable electrode welding.

PAW by rectangular pulses from a single arc power source can be obtained for the mechanized consumable-electrode wire welding with a constant feed rate. For this, it is required to use a discrete two-level switching of the volt-ampere characteristic of the power supply (PS VAC) with a bayonet section in the range of operating currents of the welding rectifier.

Let us consider how the welding electrical parameters change at a constant feed rate of the electrode wire and discrete switching of the VAC of a welding rectifier with an inverter converter (Fig.5).

[1]Lenivkin VA, Petrov PI, Oleinikov AG. *Sposob dugovoi svarki plavleniem*: *A. S. 1776517 SSSR*: [Fusion arc welding method: author's cert. no. 1776517] USSR, 1991.

[2] Oleinikov AG, Lenivkin VA, Petrov PI, Zhmailov BB. *Istochnik pitaniya dlya dugovoi svarki: RF patent 2063850* [Arc welding power source] RF Patent no. 2063850, 1994.

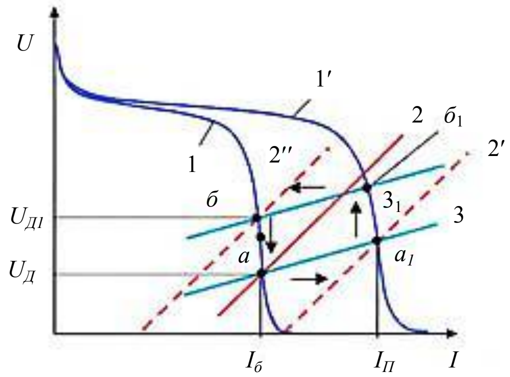


Fig. 5. Variation of mode energy parameters under PAW according to flexible program: 1 and 1' are PS VAC providing base current $I_б$ and pulse current $I_п$, respectively; 2 is the given curve of self-regulation characteristics of electrode wire melting; 2' and 2" are dummy curves of the self-regulating melting behavior of the electrode wire; 3 and 3_1 are static arc VAC before and after the current pulse action

The electrical parameters (voltage $U_д$ and arc current $I_б$) of a stable mechanized consumable-electrode wire welding are determined by the point *a* (here, PS VAC I and the characteristic line of self-regulating melting of the electrode wire 2 meet at a constant feed rate).

It is known that at any point of stable welding operation, the electrode wire feed speed ($v_п$) is equal to its melting rate ($v_э$), and the arc gap length ($\ell_д$) depends on the voltage drop across the arc and remains unchanged. Therefore, the static volt-ampere characteristic of the arc (A VAC) 3 with its constant length $\ell_д$ passes through quiescent point *a* (Fig. 5).

The current value at point *a* (see Fig. 5) is selected less than the critical current value, that is, the process of arc welding with a globular droplet metal transfer for a specific diameter and type of electrode wire corresponds to the base current of the welding process $I_б$, which is determined approximately through the dependence:

$$I_б = v_п \,/\, k_{ст}. \quad (5)$$

Here, $v_п$ is the electrode feed rate; $k_{ст}$ is the coefficient of arc current self-regulation; $k_{ст} = \frac{1}{28.3\gamma}\frac{\alpha_{пл}}{d_э^2}$ ($\alpha_{пл}$ is the electrode wire fusion coefficient, g/A h); γ is the electrode wire density, g/cm^3.

The voltage drop across the arc ($U_д$) at point *a* is selected so that PS VAC I can provide stable arc burning without short circuits of the arc gap.

Under a discrete switching of PS VAC from position 1 to position 1' and a constant arc length, the welding mode parameters of point *a* move to the position of point a_1. (In Fig. 5, the arrows indicate the direction of change in the magnitude of $I_д$ and $U_д$). The arc current value at the point a_1 corresponds to the given amplitude value of the pulse current ($I_п$), which is selected from the condition for providing the ST under its operation:

$$I_П \geq (1.5 \pm 2.0) I_{кр},$$

where $I_{кр}$ is the critical current, which is determined by the welding current magnitude, the diameter and grade of the electrode wire, the length of the arc gap.

A stable welding process with continuous arc burning at point a_1 and an unchanged arc length $\ell_д$ and $I_п$ can be established at the intersection of PS VAC 1' with the self-regulating melting line of the electrode wire 2' if the voltage drop is slightly greater than at point *a* ($v_п = v_э$). This is due to the fact that under real conditions of welding, when measuring the voltage drop across the arc, the voltage drop at the electrode wire extension is simultaneously taken into account. Therefore, an increase in the voltage drop at point a_1 is caused by an increase in the voltage drop at the electrode extension and the arc resistance at a higher current $I_п$.

When PS VAC are switched from position 1 to 1', the welding mode parameters (arc current and voltage) are determined through the intersection of PS VAC 1' and A VAC 3. In this case, the welding process is unstable since the melting rate of the electrode wire at point a_1 remains unchanged and is determined by the self-regulating melting curve of electrode 2, and $v_э$ at $I_п$ will be more than $v_п$ by the value $\Delta v_э$:

$$\Delta v_э = k_{cm}(I_п - I_б). \quad (6)$$

At that, the arc length will start to increase. The static characteristic of arc 3 will start to shift equidistantly up from point a_1 in the direction of point $б_1$.

It is established that with an increase in the arc length at a constant value of the welding current and a constant feed rate of the electrode wire, its stick out decreases, and the thermal power spent on melting the electrode decreases. The frequency of metal spray transfer decreases and the size of the transferred droplets increases. Spray transfer transforms monotonously into globular one.

When combining point a_1 with the intersection point of PS VAC 1' 'and the self-regulating melting line of electrode wire 2, a new point of stable operation with metal transfer is established, as at point a, at which $v_п = v_э$, but with a different arc length.

For PAW with ST, it is required to switch the PS VAC from position 1' to position 1 with a shorter arc length $\ell_{д3}$ than at point $б_1$, at which the ST is not violated yet.

During the arc burning on a current $I_п$ A VAC moves equidistantly from point a_1 to point $б_1$. In this case, the arc length increases by $\Delta\ell_{д1}$, and the arc static characteristic will occupy position 3_1 (Fig. 5). The voltage drop across the arc will increase by

$$\Delta U_д = k_д \Delta\ell_{д1} + k_{дт}(I_п - I_б), \quad (7)$$

where $k_д$ is the arc core voltage gradient, V/mm; $k_{дт}$ is the coefficient characterizing the slope (A VAC).

Under a discrete switching of PS VAC from position 1' to position 1, the mode parameters and the welding process go from point $б_1$ corresponding to the pulse current $I_п$, to point $б$ corresponding to the base current $I_б$. Welding at point $б$ would be stable if PS VAC intersected by the line of the self-regulation characteristic of the electrode wire melting 2, which corresponds to lower $v_п$ than the specified curve speed of the self-regulation characteristic of electrode wire melting 2.

Therefore, the melting rate of the electrode wire $v_э$ at point $б$ slows down sharply at almost constant base current $I_б$. The arc gap starts to contract since $v_п > vэ$. The arc static characteristic is shifted equidistantly from point $б$ to quiescent point a. During the arc burning at the base current, the arc length decreases by $\Delta\ell_{д2}$.

When combining the static A VAC 3_1 with characteristic 3 $\Delta\ell_{д1} = |\Delta\ell_{д2}|$, the voltage on the arc becomes equal to the specified lower level of operation of the two-level sensor. At this moment, PS VAC switches from position 1 to position 1', and the process is periodically repeated.

The pause time $t_п$ is determined by the burning time of the arc between points $б$ and a at current $I_б$, and the pulse length $t_и$ — between the points a_1 and $б_1$ at current $I_п$.

PS VAC from position 1 to position 1' and back, switches automatically depending on the specified voltage drop of the arc burning at the base and pulse current. The voltage drop is set for the base current a and pulse current $б_1$. The power supply control system receives data on the base and pulse voltages using a two-level voltage sensor. In this case, the control system of the welding power source operates according to a flexible program. The switching frequency «pulse – pause» depends on the set difference in the voltage drop between the values of the base and pulse currents.

In some cases, for example, when welding in the vertical and overhead positions, a higher flight speed of droplets is required than under the natural metal transfer. Therefore, the pulsed process should also be carried out in case when the welding current corresponds to the fine-droplet metal transfer and the following condition should be satisfied:

$$k_{нр} = f_к / f \geq 1 , \quad (8)$$

where $k_{нр}$ is the coefficient of droplet transfer irregularity, $f_к$ is the droplet transition frequency under the impact of current pulses, f is the droplet transition frequency of a natural process.

The optimal parameters of the pulse process, depending on the spatial position of the weld, should meet the conditions described by the equations (3) and (8).

The minimum pulse length providing intermittent spray transfer is (4.5–5.0) 10^{-3} s at $I_п = (1.5–.0)\ I_{кр}$. In this case, the pulse repetition rate is maximum (110–100 cps). The maximum pulse length is determined from the condition for providing ST at a constant value of $I_п$ and the maximum allowable $\ell_д$. The pulse repetition rate is selected from the condition of uniformity in the formation of the weld width along its length and should not be less than 10 cps.

Fig. 6 shows fragments of the PAW current and voltage oscillographs with intermittent spray transfer[1].

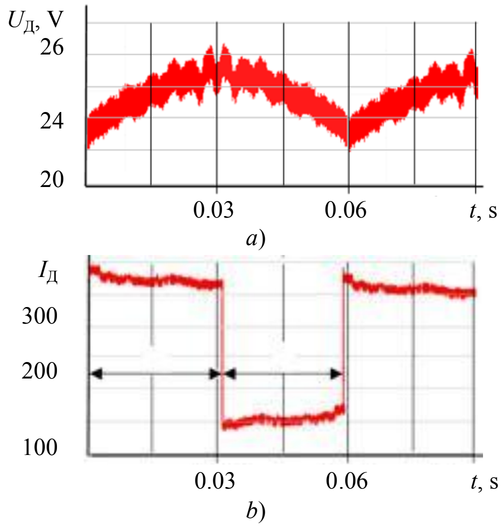


Fig. 6. Section fragment of synchronous oscillograms of PAW by rectangular current pulses with IST: (*a*) voltage, (*b*) arc current

On the oscillograms, the moment of transition of arc burning from the base current of 160A (point 1) to the pulse current ($I_п$ = 375A, point 2) is recorded. The current of 160A is less than the critical current for an electrode wire of 1.2 mm ($I_{кр}$ is 190÷200A). In this case, the current in the pulse is (1.97÷1.87) $I_{кр}$. The voltage drop across the arc at the time of switching from $I_б$ to $I_п$ is 22.8V. When the arc burns during the current pulse action, the voltage across it increases to 25.8V.

Therefore, during the action of the current pulse $t_и$ with a duration of $31\cdot10^{-3}$ s, the arc length increases by $\Delta\ell_д \leq 2$ mm, and during the arc burning by $I_б$ in a pause $t_п$ with a duration of $29\cdot10^{-3}$ s, the arc length decreases by the same amount. The pulse repetition rate is 16,6 cps.

PS VAC switches automatically from position 1, corresponding to welding at a pause current ($I_б$), to position 1_1 (corresponds to the pulse current) and back. The switching depends on the set voltage drop

$$\Delta U_д = k_д \Delta\ell_д,$$

where $k_д$ is the voltage gradient of the arc core under welding in argon at a current above critical 1.4 V/mm) between points *a* and $б_1$ (corresponds to the arc length at these points, see Fig. 5).

Using a two-level voltage sensor, the power supply control system receives information on the variation in the voltage between the base and pulse currents.

Discussion and Conclusions. Two main varieties of PAW are known. The first one is a "pulse-drop" operation: at $t_и$, equal to $(1.5–2.5)\cdot10^{-3}$ s, each pulse at the end of its action transfers one drop of electrode metal from the electrode wire to the weld pool. In this case, the processes of melting and transfer of the electrode metal are largely separated in time.

In the second type of PAW, the pulse acts much longer ($t_и \geq 4.0\cdot10^{-3}$ s and more), and the intermittent spray metal transfer occurs. In this case, the processes of melting and metal transfer are combined.

The control system of the pulse-arc welding process provides a smooth adjustment of the repetition rate of current pulses, which depends on the specified increment of the arc gap length, i.e., on the operating voltage of the two-level sensor and the amplitude of the pulse current. The repetition rate of current pulses, the duration of pulses and pauses change smoothly and are determined by incrementing the arc gap length under the action of the pulse current depending on the values of the specified current in the pause and pulse.

[1] Lenivkin VA, Kiselev DM, Dyurgerov NG. *Sposob impul'sno-dugovoi svarki: RF patent 2570145* [Pulse arc welding method]. RF Patent no. 2570145, 2015.

The flexibility of the IST program is achieved through the use of a two-level voltage sensor. The lower level of the sensor response voltage is determined by the parameters of the welding mode, which provide a stable process in a pause at a current below the critical level. The upper level depends on the elongation of the arc by 0.5–2.0 mm under the arc burning at a current that provides ST.

The developed PAW system with rectangular pulses through switching the integrated VAC-rectifier with an inverter converter is used for the mechanized welding in argon and a gas mixture (argon> 80% and CO_2 <20%) according to the rigid "pulse-drop" program and the flexible "intermittent spray transfer" program.

The study results of the capability of controlling the processing behavior of the welding arc and the proposed methods for calculating the PAW mode parameters laid the groundwork for the development of technology and equipment for the mechanized consumable-electrode PAW of aluminum alloys AMts, AMtsM, AD1, AMg6, AMg61, 01915. These developments were introduced at the enterprises of the aviation industry, shipbuilding. Solutions for stainless and heat-resistant steels and alloys are used at the motor industry enterprises.

As a result of the studies on the features of the mechanized activated electrode wire welding in carbon dioxide, the mechanized activated electrode wire Sv-08G2S PAW technology was developed for the electric furnace body units made of stainless steel X18H10T, the structural components of road-building, agricultural machines and ships. According to the scientific research results in 1985, the monograph "Equipment for pulsed arc consumable electrode welding" was published in Energoatomizdat.

The developments are protected by 17 copyright certificates and patents for inventions. Based on the research results, 31 papers were published in journals included in the list of the State Commission for Academic Degrees and Titles of the Russian Federation.

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Claimed contributorship

V.A. Lenivkin: basic concept formulation, research objectives and tasks setting, development of the theoretical foundations for pulse-arc consumable-electrode welding, academic advising. V.D. Rogozin: study on the gas-shielded pulse-arc welding self-regulation, calculation and report.

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