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# FEATURES OF ARC WITH PULSED SELF-REGULATION OF ELECTRODE MELTING PROCESS IN MANUAL ARC WELDING

**S.Yu. MAKSYMOV, V.S. SYDORUK** and **D.M. KRAZHANOVSKYI**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The article deals with the problem of providing stability of the electrode arc melting process with respect to welding or surfacing technology. It was proposed to use a current source assembled from serially manufactured components. The peculiarity of the proposed source is that it is a source of pulsating DC voltage, powered from 220V single-phase mains. It was shown that the process was equally stable both in case of mechanised welding in carbon gas, as well as during manual welding using electrodes for direct current under the conditions, which are substantially lower than those recommended by the developers of electrode materials. The proposed circuit diagram of the power source provides the ability to vary the value of the current over a wide range, which will extend the technological capabilities of welding, including larger gaps between the edges and in different spatial positions. 15 Ref., 1 Table, 5 Figures.

***Keywords:*** *self-regulation, electrode melting process, electric parameters, oscillatory character of the arc, drop overflow, complex current source, volt-ampere characteristic, oscillogram, histogram, breaking arc length*

The basis of arc fusion welding as well as related processes (surfacing, brazing, remelting) is the melting of a metal electrode under the action of the arc. Arc melting of an electrode is a nonstationary process: formation, detachment from the end of the electrode and transfer of a molten metal drop through the interelectrode (arc) gap; instability of arc length, etc. There is a problem of controlling this process to maintain its stability. The typical phenomena which mean the loss of stability are an excessive increase in the length of the arc until its natural break and a decrease in the length of the arc until a short circuit of the electrode on the workpiece.

Two possibilities of maintaining stability are known: active control and self-regulation of the electrode melting process.

Active control is known in two variants: manual and automatic.

Automatic control, as a rule, reproduces the algorithms of manual control by means of automation. In this case, in welding complex, in addition to welding unit and power source, there is a third component: process control unit. Priority in this method of welding belongs to the General Electric Company, P. Nobel (1920) [1].

Back at the time, automatic control was applied in welding with a long arc, mainly under flux, in which a short circuit of the electrode was taken as disaster — it ended in a termination of the arc process. In recent years, a considerable number of processes with automatic control have been developed concerning arc welding in shielding gases, in which the arc is periodically alternated with controlled short circuits of electrode through a molten metal drop [1].

Let us recall the most famous among them.

1. STT — Surface Tension Transfer [2]. The process was patented by the Lincoln Electric Company in 1988 and has been implemented in industry since 1994.
2. Adaptive pulsed processes of welding and surfacing by Yu.M. Saraev [3].
3. CMT — Cold Metal Transfer [4].
4. Automatic welding and surfacing using a digitally controlled power source, which is characterized by the ability to create an external (volt-ampere) characteristic in the form of a multisection broken line [5]. The authors call it a self-adaptive closed-loop automatic arc welding control system.

Automatic welding arc control provides the highest quality of welding and is irreplaceable in the manufacture of particularly critical structures, mainly of thin-sheet metal and dissimilar metals.

In mass production, as well as in case of individual production, in particular, at small enterprises, welding with automatic control is not yet competitive as compared to welding with self-regulation.

Self-regulation differs from active control in the fact, that welding complex does not contain a control unit. The stability of the process is maintained due to the fact, that power source is designed in such a way,

S.Yu. MAKSYMOV — https://orcid.org/0000-0002-5788-0753, V.S. SYDORUK — https://orcid.org/0000-0002-4746-9995

that it spontaneously reacts to the situation in the arc, and it is unambiguous: to every change in the length of the arc, and accordingly, to its voltage, it reacts by changing the current directed in the opposite direction. As the arc length decreases (at a constant electrode feed rate), the source increases the current, due to which the electrode melting rate grows and the arc length is increased to a preset value. In the case of an increase in the value of the arc length against a preset one, the response of the source is the opposite: the current is decreased, and accordingly, the melting rate of the electrode is reduced.

The principle of self-regulation of the arc was proposed by V.I. Dyatlov at the E.O. Paton Electric Welding Institute in 1942 [6].

However, the «classic» method of self-regulation has a serious drawback: it works, as was shown by B.E. Paton [7], only at a sufficiently large current density on the electrode. On the basis of production experience, we found that the minimum possible current density (in automatic submerged-arc welding with the use of a low-carbon wire of 5 mm diameter) is equal to 30 A/mm$^2$. During welding in shielding gases, it may exceed 100 A/mm$^2$.

It became necessary to develop such an algorithm for self-regulation of electrode melting, in which the stability of welding process would be high with a decrease in the current density at the electrode, at least as that in manual arc welding (12 A/mm$^2$). It means that in welding using a wire of a «large» diameter at low speed of its feeding, the arc should neither break during an accidental increase in its length, nor extinguish in a short circuit during a decrease in its length.

We followed the path of combining the properties of manual arc welding in a one process (the VAC$_s$ should be steeply drooping, where $U_{o\text{-}c}$ is several times higher than a preset $U_a$) with the property of mechanized welding, where the VAC$_s$ should be flat drooping, and $U_{o\text{-}c}$ does not much exceed the set value of $U_a$. It is rather difficult to prevent the oscillations of arc parameters. But if we «damp» them, we turn them into a tool of technology. How did we managed to do that? We powered arc simultaneously from two sources: with steeply drooping VAC$_s$ both for manual arc welding as well as with a flat drooping — as in mechanized one.

Since the change of electrical parameters — voltage and current in the welding process is pulsed, the proposed type of self-regulation was called pulsed [8].

One of the characteristic features of such an arc is its oscillatory character: the length of the arc decreases periodically — sometimes (if necessary) — to a short circuit, then it increases again (which is related to the detachment of an electrode metal drop formed at the end of melting electrode and its transfer to a metal pool). During the period of arc shortening (as a rule, it coincides with the period of formation of a molten metal drop at the end of the electrode) the welding current increases, and if a drop was not able to detach from the electrode, it touches a metal pool, «freezing» of the electrode does not occur due to the already jump-like increase in current at the moment as compared to a «normal» amplitude.

That period is essential during the cycle of arc length oscillation. Unlike the process of melting the electrode at a long arc, when a drop detaches from the end of the electrode and is transferred to the welding pool through the electrode gap, here, a drop «flows» from the end of the electrode directly into the metal pool. This occurs in welding on a short arc with periodic short circuits, and the melting of the electrode at such moments does not stop, otherwise, the electrode would «frozen» to a welded product. In contrast to a pure arc melting, here in the periods of short circuits another process occurs — contact melting [8]. The periods of arc and contact melting alternate with the frequency of short circuits of the electrode.

The process of contact melting can be controlled. For this purpose in the electrical circuit diagram of the power source it is necessary to provide a third component, so to speak, a third source. Its main characteristics are the following: low open-circuit voltage (not more than the sum of cathode and anode voltage drops), rigid volt-ampere characteristic, high short-circuit current.

Such an algorithm is extremely effective for mechanized arc welding at a constant electrode feed rate, where the minimum allowable current density at the electrode can be reduced by several times, and sometimes by an order of a value, as compared to traditional mechanized welding.

However, the same algorithm turned to be a quite useful and required for manual arc welding/surfacing by coated electrodes.

The affinity of algorithms of power source response on situation in the arc for mechanized arc welding/surfacing on the one hand and for manual one on the other, opens a good perspective for building universal power sources suitable for both mechanized as well as manual arc welding with appropriate choice of parameters for power source response.

Moreover, it turns to be possible to create a power source for DC welding/surfacing (more precisely with a current of straight polarity) which is connected to a single-phase 220 V mains (in fact, «household» mains), which can attract the interest of a wide range of users and not only industrial enterprises.

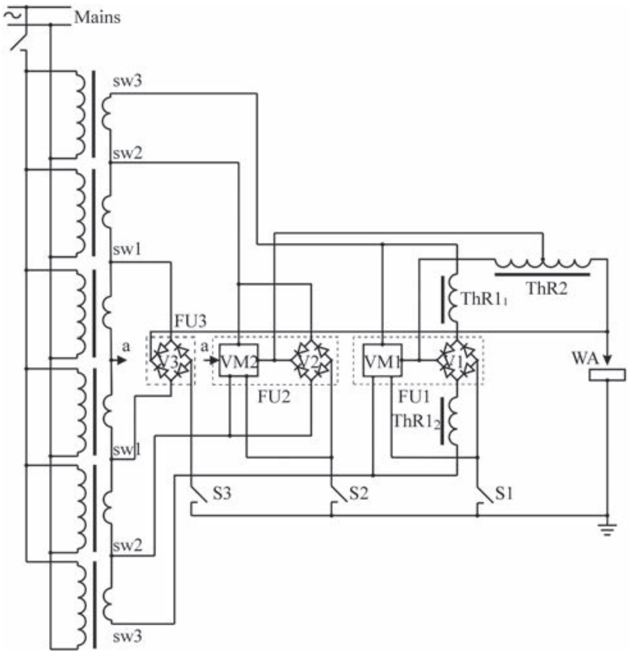

**Figure 1.** Scheme of the proposed «composed» power source

This paper presents the results of experiments using a source of straight polarity which is connected to the 220 V «household» mains based on, attention!, three transformers of serial production with a rigid volt-ampere characteristic and low open-circuit voltage of 14V: two OSM1 — 1.0 kVA and one OSM1 — 1.6 kVA.

Below, one of the variants of the scheme of the proposed «composed» power source in the variant with three low-voltage transformers on a secondary voltage of 14 V is given, which served as the basis for the three functional units FU of the «combined» source (Figure 1). Those units differ in the shapes of volt-ampere characteristics: the first has a steeply drooping shape with an elevated open-circuit voltage $U_{\text{o-c}}$ of the arc, which provides a constant arc burning at a low current at its increased voltage, the second flat drooping shape with a medium voltage $U_{\text{o-c}}$ which provides a steady burning of the arc at a set «working» current and the third one is with a rigid volt-ampere characteristic, which provides a «hot start» and contact electrode melting. Transformers are parallel-connected to the electric mains by primary windings and their secondary windings are series-connected, due to which their secondary voltage (open-circuit) is multiplied by the total number of secondary windings. Since each transformer has two secondary windings with a voltage of 14 V and there are 3 such transformers, the total open-circuit voltage of all the secondary windings is 84 V. Together with the rectifying unit R1 and the voltage multiplier VM1, those windings form the functional unit FU1. The multiplier VM1 is used when it is necessary to additionally raise the $U_{\text{o-c}}$ of the source. A «steep drooping» of the VAC is created by the throttle $\text{ThR}_1$ and additionally by the $\text{ThR}_2$.

The second functional unit $\text{FU}_2$ with a flat drooping VACh contains 4 series-connected secondary windings of transformers, rectifying unit R2, and a part of windings of the throttle $\text{ThR}_2$.

The third functional unit FU3 with a rigid VAC contains 2 series-connected secondary windings of transformers and rectifying unit R3.

Again it should be noted that the mentioned voltage multipliers are used when in order to increase the process stability, it is necessary to raise the open-circuit voltage on the corresponding functional unit of the power source.

Since the experimental composed assembled power source has a single-phase connection and that in the periods of changing the polarity the current drops to zero, it can be assumed that the stability of the electrode melting process should be low, which makes the power source unsuitable for welding. However, the experiments have shown that this «non-standard» source provided a steady process both for manual welding as well as for mechanized one in carbon gas.

The coated electrodes were used, which are suitable both for DC welding (UONI-13/55, OZL-8) as well as for AC welding (ANO-24).

Simultaneously, for comparison, the experiments with the power from the serial rectifier VDU-306 were carried out.

The procedure of experiments consisted in the fact that in the process of arc burning with the help of the information-measuring system IBC, oscillograms of the arc current and voltage were recorded at a frequency of 10 kHz (Figures 2, 3). The system processed those parameters by using the special software and on request it provided a graphical display of their specific values in the coordinates *U*–*I*, recorded at different moments (the latter was called the volt-ampere characteristic of the electrode melting process) (Figure 4). In addition, the system generated histograms of those parameters (a number of their fixed values depending on the amplitude) — Figure 5.

The interpretation of such patterns is given below.

Figure 2 presents the current and voltage oscillograms for the electrodes of the grade ANO-24 of 3 mm diameter with the power from the experimental source, and Figure 3 shows oscillograms for the electrodes OZL-8 of 3 mm diameter with a power both from the experimental source (Figure 3, *a*) and from the serial VDU-306 (Figure 3, *b*).

In the Figures one can see the «wave-form» nature of the oscillograms, especially, of the current ones.

As can be seen from Figure 2, the arc oscillations are not strictly periodic, their frequency ranges from 9 Hz (see the moment of 9.5 s) to 23 Hz (the moment of 9.75 s). Short circuits through electrode metal

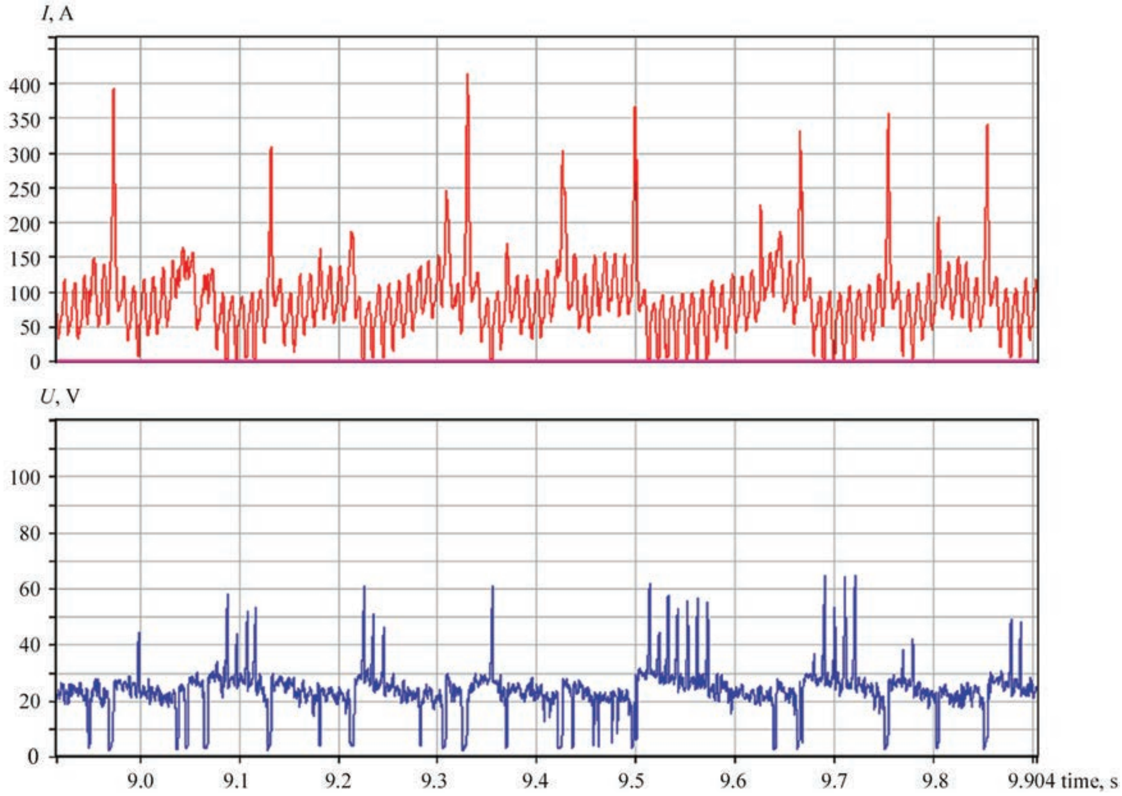

**Figure 2**. Current and voltage oscillograms of the process of welding using the electrodes of the grade ANO-24 of 3 mm diameter

drops occurred at 8.97; 9.136; 9.33 s etc. At the time when the «ordinary» amplitude of the arc current was 150 A, the value of the current pulses at the moment of closing a drop on a metal pool, as a rule, exceeded 250 A and reached 450 A (for example, the moment of 9.33 s), despite the fact that an average current value was about 80 A, i.e. the current pulses at the moments of short circuits exceeded the average current value by 3.0–5.6 times. Naturally, with such current pulses, «freezing» is out of the question.

A sawtooth pulsed nature of the oscillograms with a frequency of 100 Hz corresponds to the industrial frequency of current of 50 Hz.

The welding voltage during the process of arc oscillation was within the range of 20–30 V, except of some «moments»: to the values of about 4 V at short circuits.

The remarkable stability of the arc with such a «torn» shape of current and voltage oscillograms, which can be seen in Figure 2, contradicts with existing canonical notions about the arc stability: the continuity of current and voltage oscillograms at slight deviations from the mean value, especially with respect to arc voltage, and raises the problem of formulation of stability conditions for the electrode melting process during arc welding with a pulsed self-regulation of this process.

The oscillation process of electrode melting described above has a technological and industrial profit from several points of view.

First, the oxidation of electrode metal drop by the arc atmosphere is decreased by reducing the length of its «free run» through the arc gap. Secondly, the alternation during the cycle of oscillation of the arc of elevated current — at shortening, and elevated voltage — at elongation of the arc provides, on the one hand, reliable penetration of the base metal and on the other hand — acceptable formation of a weld bead. Thirdly, the shift of the mode to the region of lower voltages creates the prerequisites for reducing the electric power consumption (energy saving).

The latter is illustrated by the results of experiments with the use of electrodes OZL-8 of 3 mm diameter. Welding was performed from two sources alternatively (for comparison): from the experimental and serial VDU-306. In Figure 3, *a* the oscillograms of current and voltage obtained during welding from the experimental source are shown, in Figure 3, *b* — the same from the serial VDU-306 are shown. It is seen that as compared to the experimental source, the arc from VDU-306 is characterized by oscillations in current and voltage with negligible amplitudes, which indicates the welding mode on a long arc. The exceptions are episodes in the time intervals close to 8.59657 and 8.62 s, and also between 8.84 and 8.86 s — short circuits through the electrode metal drops (frequency of short circuits is about 4 Hz).

The comparison of volt-ampere characteristics of the processes (Figure 4, *a*, *b*) allows establishing sig-

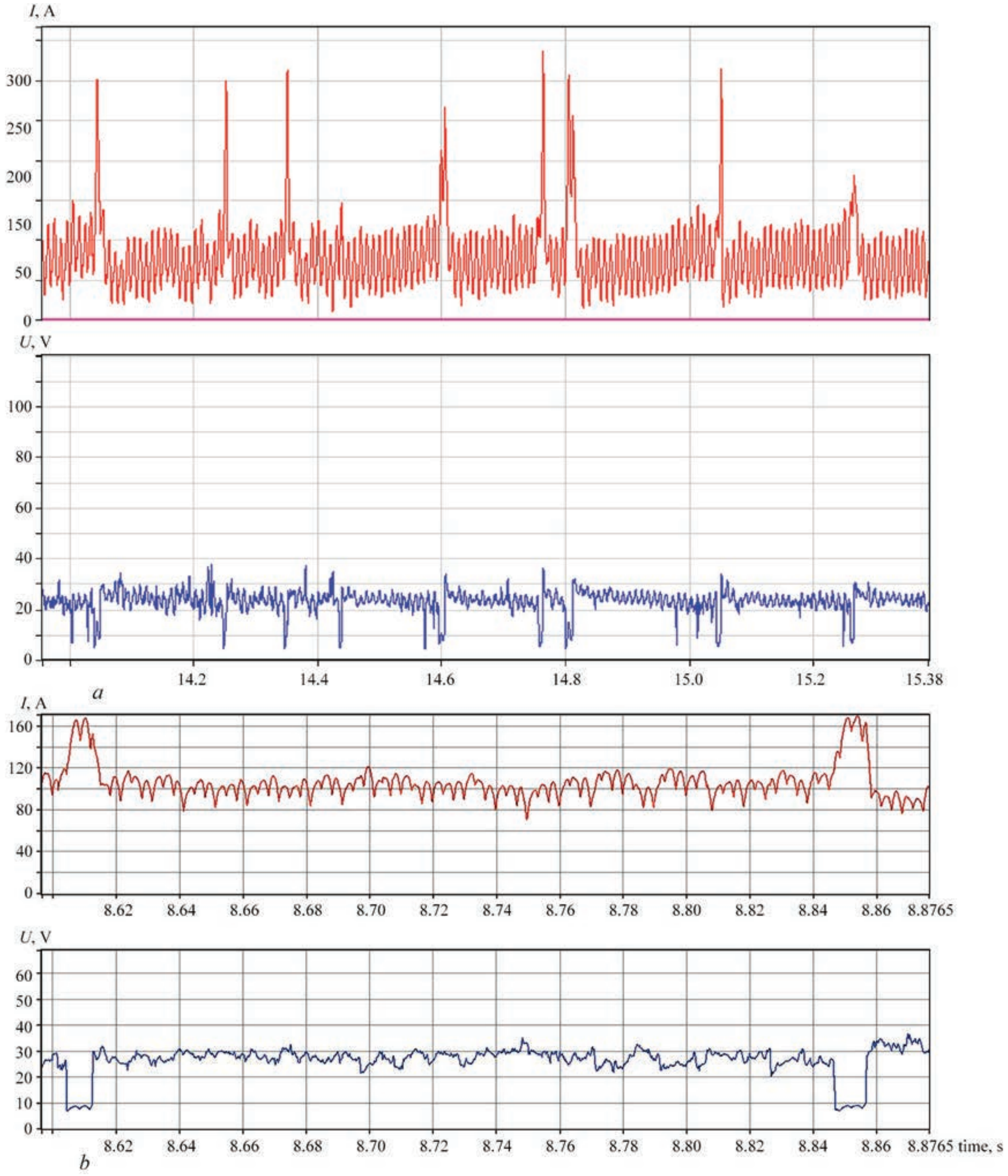

**Figure 3.** Current and voltage oscillograms obtained during welding from the experimental power source (*a*) and the power source VDU-306 (*b*) using the electrodes OZL-8 with a diameter of 3 mm

nificant differences between them. If during welding from VDU-306, the region of existing modes is located in the voltage interval of 18–38 V in the range of welding currents from 70 to 125 A at an average current value of about 97 A (Figure 4, *b*), then the similar indicators for the experimental source are 13–30 V, and the current is 30–160 A at a mean value of current of about 88 A. It is seen that the region of modes from the experimental source is located much lower, than from VDU-306. Thus, at a current of 75 A, the arc voltage was at different moments on the experimental source in the region from 13 to 30 V (on average — 21.5 V) (Figure 4, *a*), and from VDU-306 — respectively from 28 to 36 V, on average — 32 V, (Figure 4, *b*), i.e. almost 1.5 times higher. Accordingly, the energy consumption on the arc at the same current during welding from VDU-306 is 1.5 times higher than from the experimental source.

Another feature of the compared modes: during the use of the experimental source, the fraction of energy spent on melting the electrode at the moment of short circuits (which is called contact melting, that region of the melting mode is located separately in the lower part of the volt-ampere characteristic in the form of an ascending dark band) is much larger than from VDU-306: here it covers the range of short circuit currents from 75 to 325 A, while from VDU-306 — it ranges from 115 to 170 A. As far as the voltage drop at short

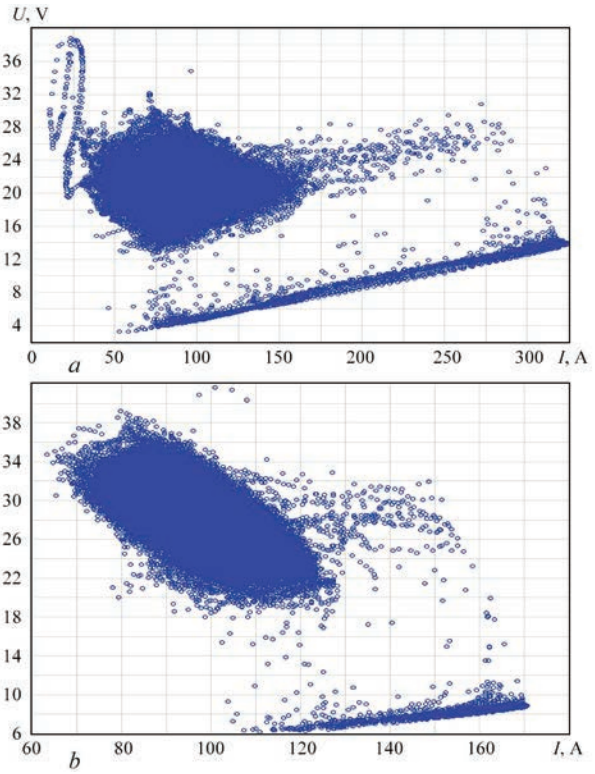

**Figure 4.** Volt-ampere characteristic of welding process from the experimental power source (*a*) and the power source VDU-306 (*b*) using the electrodes OZL-8 with a diameter of 3 mm

circuits is in 2.6–5.0 times less than that of the arcs at the same current values, the consumption on contact melting is lower than that on the arc. And this is an additional channel for saving electric power.

Below a table of characteristic arc parameters for experimental welding at the minimum «set» values of welding current for electrodes of different grades of 3 mm diameter with a forced arc break is given.

From the Table it follows that the «set» value of the low-ampere arc current during welding from the experimental source is significantly lower than the limit of its rated value for the three mentioned grades of electrodes given the fact, that the arc length at the moments of forced breaking is significantly larger than the standard value of 2–4 mm.

It should be noted that in all cases of welding listed in the Table, the arc ignition was reliable (despite a low «set» current value) and the arc burning was stable.

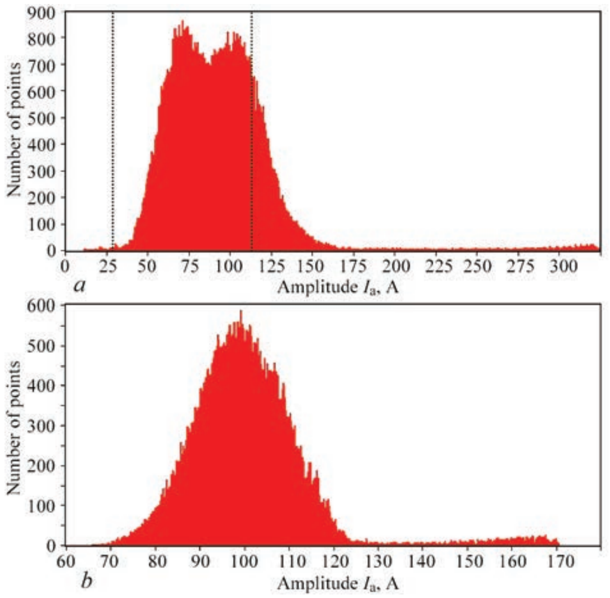

**Figure 5.** Histogram of current of welding process using the electrodes OZL-8 powered by the experimental power source (*a*) and the power source VDU-306 of serial production (*b*)

Here is just one variant of the technology being developed: manual arc welding. Some results of experiments using experimental («self-made») single-phase («household») DC source and the one assembled from products of serial production are shown: step-down transformers with a rigid volt-ampere characteristic, with a low open-circuit voltage of 14 V, which is not inherent for welding technology (commonly used in control systems), diodes (possible thyristors), throttle, etc.

Today some other variants of the developed technology have been worked out: mechanized arc welding with a constant electrode wire feed rate, with twinned electrodes, with a combination of plate and wire electrode, etc.

Some encouraging results have been obtained: the burning of alloying elements and the consumption of electric power are reduced, the microstructure of weld metal and near-weld zone is refined, etc.

A part of the proposed technical solutions is protected by patents ([9], [15]).

Characteristic parameters of the arc during experimental welding

| Electrode grade | Arc parameters | | | | |
|---|---|---|---|---|---|
| | «Set» values | | Values at the moment of arc break | | |
| | Arc current $I_a$, A | Arc voltage $U_a$, V | «Breaking» length of the arc $L_a$, mm | «Breaking» voltage $U_{b.a}$, V | «Breaking» current $I_{b.a}$, A |
| ANO-24 | 63 | 23 | 18 | 38 | 36 |
| UONI-13/55 | 68 | 23 | 16 | 40 | 40 |
| OZL-8 | 68 | 23 | 14 | 40 | 40 |

It can be noted that similar phenomenon is observed also in electroslag welding.

## Conclusions

1. Experiments on welding using coated electrodes of different grades, powered by an experimental source, built in accordance with the principle of pulsed self-regulation of the arc, showed a good excitation of the arc, even under the condition of a small set rated current, which is provided by a higher value of short circuit current — up to 450 A , as well as good arc stability, which is confirmed by its large length at the moment of forced breaking — up to 14–18 mm as compared to the normative value of the arc length of 2–4 mm, despite the fact that the arc current was below its rated value.

2. As far as the experiments were successful with the use of DC source (more precisely, current of direct polarity) powered by a single-phase 220V («household») mains, small enterprises and physical entities can be users of such a source and of the proposed technological solutions.

3. The technology assumes the ability to perform welding on currents substantially lower of their rated value, maintaining an excellent excitation and a good arc stability, which in some cases provides elimination of the use of scarce electrodes of small diameter.

4. The ability to vary the value of current over a wide range allows extending the technological capabilities of welding, including larger gaps between the edges, in different spatial positions, welding of dissimilar metals, surfacing, etc.

5. As the parameters of the arc at equal currents from the experimental source are displaced in comparison with VDU-306 in the region of lower voltages, the developed technology provides a real opportunity to save electric power.

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