Hybrid method of controlling arc welding process with consumable electrode and related processes

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Abstract. For the development of a classical method of mechanized arc welding with a self-regulation of the process of melting the electrode supplied to the welding zone at a constant speed, the following combination was proposed: on the one hand, a digital power source with automatic control and programming of volt-ampere characteristics VAC, which is a two-step one in our case: a – for increased arc length (with a low current), b – for shortened arc (with a high current); on the other hand, self-regulation of the melting process by the corresponding reaction of the power source. Moreover, the electrode melting occurs in a programmed oscillatory mode between the extreme values of the arc length: maximum and minimum. Such a combination is called a hybrid method of controlling the process of arc welding with a consumable electrode.

1. Introduction
The basis of arc fusion welding, as well as related processes (surfacing, soldering, remelting), is the melting of a metal electrode under the action of an arc. Arc melting of an electrode is a non-stationary process: formation, detachment from the end of the electrode and transfer of molten metal droplets 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.

2. Electrode melting process
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 the welding complex, in addition to the welding unit and power source, there is a third component: process control unit.

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, 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 decreased. Such reaction of the source occurs due to the specificity of its external (volt-ampere) characteristics, which is expressed graphically in the form of a curve in the coordinates I – U (VAC).

The process of self-regulation of the arc takes place also during manual arc welding. Below the characteristic VAC, are presented for manual arc welding (figure 1 a) and for mechanized arc welding with self-regulation (figure 1 b).

![Figure 1](image1.png)

**Figure 1.** VAC, typical for manual (a) and mechanized arc welding with self-regulation (b)

Designations: VAC – volt-ampere characteristics of welding current source; Uoc – open-circuit voltage of current source; Ish.c – short-circuit current of current source; A – point on the VAC curve, corresponding to the accepted mode; Ua – preset arc voltage; Ia – preset arc current; AUsh – change in arc voltage at its shortening; AU – change in arc voltage at its elongation; ALsh – change in arc current at its shortening; AL – change in arc current at its elongation; VACw.h. – volt-ampere characteristics of welding head.

In manual arc welding, welder maintains a preset length of the arc and, accordingly, its voltage constant. The function of the source is maintaining the arc current constant. It is provided by steeply falling VAC. At very significant fluctuations in the length (voltage) of the arc ΔU, the arc oscillations ΔI are negligible. The element of self-regulation is the constancy of the current, which is evident.

The preset arc current Ia is established at the source by a corresponding change in the short-circuit current Ish.c. A dotted line in figure 1a shows VAC in case of decreasing Ia to the value Ia1. The arc voltage Ua1 corresponds to it.

In figure 1b, the preset welding mode with self-regulation is indicated by a point A – the intersection of the curve of VAC and VACw.h (welding head). Here, the preset arc current is established at the welding head: the larger the cross-sectional area of the electrode and its feed rate, the larger the preset welding current I1 (and vice-versa). In this case, even with a slight decrease in the arc length and, accordingly, in its voltage ΔUsh, the welding current ΔIsh increases significantly, due to to which the melting rate of the electrode grows and the length of the arc is increased and vice versa. This occurs because VAC represents a flat falling curve. Here, the self-regulation of the electrode melting rate is an oscillatory process, which we previously called self-modulation [1].

The preset arc current I1 on the welding head is reduced by a corresponding change in the electrode feed rate. A dotted line in figure 1b shows VACw.h.1 for reducing I1 to the value I11. To this value, a set reduction in the open-circuit voltage of the power source to Uoc.c.1 corresponds in order to provide the necessary arc voltage reduction to Ua1.
Historically it formed so that, at first, **automatic control** of the electrode melting process was developed. As in manual arc welding, its function consisted in maintaining a constant arc length. The automatic control system continuously measured the arc voltage (arc length indicator), which is an adjustable parameter. With an increase in the arc length, the system generated an electrical signal supplied to the motor of the electrode wire feed mechanism to increase its feed rate (regulating effect). After the arc voltage was restored at a preset value, the signal to increase the wire feed rate was stopped. When reducing the length of the arc, the system generated a signal to reduce the electrode wire feed rate. As a result, the average wire feed rate was equalized with the rate of its melting. As in manual arc welding, the arc current was increased at the power source. As far as with an increase in the arc current, the melting rate of the electrode wire was increased, the system accordingly increased its feed rate. The priority of this method of welding belongs to the company General Electric Company, P.Nobel (1920) [2, p. 180]. The systems for the process control, described above were objectively in a state of interaction, competing and simultaneously complementing each other.

**Automatic process control** provides an accurate performance of the preset algorithm and is characterized by an excellent quality of the welded joint. Its main drawback is the complexity of the device and a high cost of the equipment, as well as additional costs for maintenance of the equipment. This method of control is challenging during the manufacture of critical structures, as well as in the case of special welding processes.

**Self-regulation of the electrode melting process** is free from the disadvantage mentioned above. However, it lacks its main advantages like adaptation to the welding conditions and the ability to fulfill the special technology requirements. The range of mode parameters here is essentially narrower. And here is another disadvantage of self-regulation principle: as B.E. Paton showed, self-regulation is possible only at a very significant current density on the electrode [3]. Based on the production experience, we found that the minimum possible current density on the electrode is 30 A/mm².

An explanation to this fact is given in figure 1b, where dotted lines show the positions of VACₚ and VACₜ for the case of an excessively low value Iₜ₁. Here, the open-circuit voltage of the power source is so low that the sum Uₜ₁+ΔUₜ exceeds the value Uₗₚₙ₁, and the arc is broken. This fact limits the technical capabilities of the method and increases its cost.

It became necessary to develop such an algorithm for self-regulation of electrode melting, at which the stability of the welding process would be high if the current density on the electrode decreased, at least as in manual arc welding (7 A/mm²).

It was decided to use the oscillatory nature of the electrode melting process [1]. It was proposed to perform electrode melting in an oscillation melting mode which is expanded in the amplitude of control, i.e. at an increase in the arc length (voltage) to higher than a preset value, to power it with the current, at which the melting rate is substantially lower than the feed rate and to increase the current to a value, at which the melting rate of the electrode is much higher than its feed rate after the inevitable decrease in the arc length (voltage), lower than a preset pulse [4]. Such current manipulations occur due to the spontaneous reaction of the source, having a specific VACₚ (figure 2).

![Figure 2](image)

**Figure 2.** VACsource for realizing oscillatory nature of the electrode melting process

Designations: VACₚ is a steeply falling region of volt-ampere characteristics; VACₚₘ is a rigid area corresponding to the parameters of a «long» arc; VACₚₙₚ is a rigid area corresponding to the parameters of a «short» arc; VACₚ is the volt-ampere characteristics of a welding head; Iₚ is the current of a «long» arc; Iₚₙₚ is the current of a «short» arc; Uₚ is the «long» arc voltage; Uₚₙₚ is the «short» arc voltage.
If it is necessary to reduce the mean current value, the current of a “long” arc \( I_{\text{sh.a}} \) should be reduced up to several amperes due to the “supporting” action of the steeply falling VAC\(_{s.f.} \). At the same time, the minimum required current value of a short arc \( I_{\text{sh.a}} \) is maintained, which is sufficient to accelerate the melting of the electrode and to prevent a short circuit.

The feature of VAC of such a source consists in the fact, that the voltage \( U_{\text{sh.a}} \) can be reduced to a value lower than the sum of the cathode and anode voltage drops. In this case, the arc does not burn, and the electrode melts in a metal pool due to the contact melting phenomenon [5], and also through a drop of molten metal at the end of the electrode.

For the experiments, the source LET-500 [6] with a digital control was used, where VAC\(_s \) of any shape can be programmed.

Here, the combination of self-regulation of the electrode melting process due to the specific reaction of the power source to the situation in the arc and of automatic control of the source is clearly seen. Such a combination can be called a hybrid method of process control. It allows providing the stability of the electrode melting process in almost the whole range of welding/surfacing technology: from manual arc welding, including welding with a fire-crack electrode at a low current density, to a mechanized arc welding with both long and short arc in any environment, including the process of electrode melting with a controlled transfer of molten metal droplets during short circuits.

The disadvantage of this method is an increased spattering of electrode metal caused by the explosion of a liquid metal bridge between the end of the electrode and a molten metal droplet absorbed by the metal pool under the electrodynamic influence of the pinch effect. This disadvantage was radically reduced by the automatic control of all stages of the process of a droplet formation and its transfer into a metal pool. The features of such formation and transfer were well studied by that time [7], mainly at the E.O.Paton Electric Welding Institute of the NAS of Ukraine.

In the world, a significant number of methods of arc welding with automatic control is known [2, 8]. As a rule, they all develop the method developed at the PWI by A.G. Potapievsky [9], where a current source is used, having combined volt-ampere characteristics consisting of two regions: “upper” – steeply falling (at elevated voltages) and “lower” – flat falling.

Let us recall the most “advanced” methods with automatic control.

1 – “adaptive pulsed processes of welding and surfacing” [10], proposed by the Institute of Strength Physics and Materials Science of the Siberian Branch of the Russian Academy of Sciences, patented in 1984;

2 – STT [11] - “surface tension metal transfer”, patented by the Lincoln Electric Company in 1988, it has been implemented since 1994;

3 – CMT [12, 13] - “cold metal transfer”, known since 2002

The physics of the process is the most adequately reflected in the work (1). In the work (2), the distinctive “brand” point is the term “surface tension transfer”, which is perceived as an obvious semantic “tension”, since the main “driver” of a drop “transfer” here is the electrodynamic pinch effect. In the work (3), “for the sake of the brand”, another liberty was admitted – the introduction of the term “cold metal”, although the cooling of metal is not performed, but the electrode is pulled away from the metal pool. Another distinctive point is a rhythmic change in the electrode polarity.

In the listed works it is not mentioned about the volt-ampere characteristics, except for the work (1), where the use of serial production power sources with standard VAC\(_s \) and about the presence of thyristor pulsed regulators in the welding circuit, controlling the algorithms of adaptive changes of electrical parameters at all stages of electrode melting.

In the work [14] it is reported about VAC\(_s \) of a special shape in the form of a multilink line consisting of a set of straight lines intersecting at different angles. The automatic control system activates the VAC regions depending on the electrode melting stage.

The mentioned technical solutions for automatic control of the welding/surfacing process are related to a comparatively narrow area of technology: in shielding gases at a low current density on the electrode for the cases of formation and transfer of electrode metal droplets. For the technologies with fine-drop and jet transfer of electrode metal, they are not suitable. In small-scale and individual
production, the priority is given so far to the technology with self-regulation of the electrode process and its latest version: with pulsed self-regulation.

3. Conclusion
Recently, interesting perspectives are opened up for hybrid methods of process control in which universal inverter power sources with digital control are used, on which VAC of any desired shape is programmed. This is the most promising approach for today for solving different problems arising in production. The rich possibilities of such an approach have not yet been disclosed. In particular, by reprogramming of VACs, a pure arc process with pulses on a short arc without sh. c. (see oscillogram figure 3), arc process on a long arc, having its advantages, arc process with jet electrode metal transfer, etc. can be obtained.

![Figure 3. Oscillogram of the welding process with pulses on a short arc without short circuits.](image)

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