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PROCESSES OCCURRING AT EXCITATION OF THE WELDING ARC (Review)

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In view of the fact that a complete theory of the process of welding arc excitation, which could provide a convincing explanation of the entire totality of the known facts is absent so far, some important theoretical and experimental data of different authors are considered as regards the processes of initial excitation of the welding arc in arc and plasma welding which is important for designing electronic boosting devices, generating pulses of high and higher voltage that are injected into the interelectrode gap to ensure contactless initial and repeated excitations of the welding arc. Requirements to pulse parameters that are generated by these devices are given, which are obtained on the base of many investigations (including theoretical studies), experience in designing and application of boosting devices. Analytical expressions are proposed to create the theory of the process of DC welding arc excitation. 15 Ref.

Keywords: welding arc excitation in arc and plasma welding, glowing, spark and arc discharges, initial ignition voltage, repeated excitations of AC arc, combined devices - exciters-stabilizers, energy, amplitude, pulse duration

Contactless welding arc excitation is one of the most important stages in the welding cycle, which in most cases is carried out by a high-voltage breakdown of the interelectrode gap due to the use of a spark discharge. Despite a significant interest of researchers in the spark discharge, the theory of this process is still absent. According to the established concepts of modern electrophysics, the spark discharge (as a result of which excitation of the welding arc is carried out) refers to a nonindependent anomalous glowing discharge, which at the time of its completion should pass to a constant arc one [1, 2]. According to these concepts, temperature and gas pressure in the spark channel, the temperature of gas in this channel can reach 10000 K, which causes the probability of thermal ionization, and the phenomena that occur during a spark discharge, are explained in the theory of streamers (plasma channels threading from the anode to the cathode of the gas gap) [1]. As is noted in [1, 2], when an electric field is applied to a gas interelectrode gap, the charged particles present in this gap are accelerated by this electric field, and it should be noted that since the mass of ions significantly exceeds the mass of electrons, the main role in their interaction belongs to the electrons. If the electrons energy is sufficient for the gas ionization, a number of charged particles will increase, and in the direction from the cathode to the anode electron avalanches will move, leaving a positive spatial bulk charge and at the same time random electrons and the electrons formed in the gas during photoionization as a result of the radiation of atoms and molecules excited by electrons, will be drawn into the zone of spatial charge, creating new daughter avalanches on its way [1].

The first condition for the streamers formation is:

$$\frac{\alpha}{p} e^{\frac{\alpha}{p} pd} = 2{,}19 \cdot 10^8 \frac{E_g}{p} \sqrt{\left(\frac{d}{pd}\right)} \cdot d, \qquad (1)$$

where α is the volume ionization coefficient, m^{-1}; ρ is the gas pressure, Pa; d is the distance between the electrodes, m; E_g is the intensity of electric field between the electrodes.

Using the expression (1), it is possible to find the value of the spark breakdown voltage U_g by the expression:

$$U_g = E_g d, \qquad (2)$$

However, the values, calculated by this expression coincide well with the experimental ones only in the cases when $pd \geq 250$ MPa, which is almost nonexistent in arc or plasma welding.

The second condition for the streamer formation is the formula

$$n_i \geq 7 \cdot 10^{20} \text{ ion/m}^2, \qquad (3)$$

where n_i is the concentration of ions in the avalanche head.

For relatively short spark gaps (which is characteristic of arc and plasma welding), the condition (3) is always realized in case, if the condition (1) is realized.

The approximate theory of the spark discharge is usually based on Toepler's hypothesis, according to which the conductivity of the spark channel is proportional to the charge passed through the interelectrode gap:

$$G = k \int_0^t i\,dt, \qquad (4)$$

where G is the conductivity of the spark channel, Ohm^{-1}; k is the coefficient of proportionality, which depends on the composition, temperature and pressure of the gas

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in the spark channel. Or the hypothesis of Weizel and Rompe, according to which all the energy released in the spark channel is spent to increase the internal energy of the plasma and is proportional to the conductivity of the spark channel and in this case [1]:

$$G = k\left(\int_0^t i^2 dt\right)^{1/2}. \qquad (5)$$

However, it should be noted that both mentioned hypotheses (4) and (5) describe the initial stage of the spark discharge process and do not take into account the decrease in the conductivity of the spark channel at the final stage of the process.

In turn, the hydrodynamic theory at a pulse energy, which is characteristic of spark ignition of the welding arc, leads to the following dependence of conductivity on the voltage at the interelectrode gap:

$$G = kCl^{-7/3}\left(U^2 - u^2\right)^{3/2} \times$$
$$\times\left[6U^4 \ln\frac{U}{u} - \frac{3}{2}\left(U^2 - u^2\right)\left(3U^2 - u^2\right)\right]^{-1/6}, \qquad (6)$$

where C is the capacitance directly connected to the spark gap, F; l is the length of the spark gap, m; U is the initial voltage on this gap, which is approximately equal to the breakdown voltage, V [1].

The longitudinal electric field strength in the spark, which precedes the formation of a constant arc discharge, characterized by relatively large values of current (up to 10^4 A) and current density at the cathode (up to 10^{10} A/m^2) at a relatively low arc voltage (from several units to tens of V), amounts to several kV/cm [1–4].

Thus, it was established [1–3, 5–7] that a streamer can be formed in a gas plasma, in which usually the chaotic movement of charged particles is dominated over their directional movement under the action of electric field or as a result of diffusion. Here the following equality should be realized

$$U = U_c + U_P + U_a, \qquad (7)$$

i.e., the streamer formation depends not only on the composition, temperature and pressure of the gas in the interelectrode gap, but also on the state and phenomena occurring in the near-electrode regions and the welding arc column.

The distribution of the electric potential along the length of the interelectrode gap is given in [1–6, 8, 9], and in [9] the phenomena at the anode and in the column of a multicurrent welding arc are analyzed in detail and comprehensively, and mathematical models based on the basis of this analysis, as a result of which the author assumes that the plasma potential of the arc column at the boundary with the anode layer is inhomogeneous, i.e. depends on the coordinate along the specified boundary. This causes the appearance of the component of the gradient of the electric potential and, accordingly, the components of the current density along the boundary of the anode layer, which largely determines the picture of the flow of electric current between the arc plasma and the anode.

To describe the plasma adjacent to the anode surface, the author of [9] conventionally divides the near-anode plasma into several zones. The first of them, which is directly adjacent to the anode surface, is the sheath, where the condition of the plasma quasineutrality is violated and a part of the potential drop between the plasma and the anode is formed. However, this can be neglected, taking into account that at a pressure close to the atmospheric one, and at the values of plasma temperature close to 1 eV, typical for arc or plasma welding conditions, the thickness of this layer is commensurable with the Debye radius, which amounts approximately to 10^{-8} m, which is significantly less than the free path lengths of the particles of the near-anode plasma, which range approximately from 10^{-7} to 10^{-4} m.

The second zone, the ionization layer or presheath, is a region of nonisothermal quasineutral multicomponent plasma, where charged particles are generated by ionizing plasma electrons of gas atoms desorbed from the anode surface and by the atoms of the anode metal which is evaporated. The ions formed in this zone, are accelerated in the direction of the anode surface by the electric field generated by more mobile electrons and recombine near this surface and thus, within the presheath, the conditions of a local ionization equilibrium are violated, i.e. the concentration of charged particles $n_e = n_i$ differ from the equilibrium concentration nSa, calculated using the Saha equations. In addition, here a noticeable drop in the potential of the near-anode plasma occurs, which can be much larger than its changes in the sheath.

According to the opinion of the author of [9], the outer boundary of the anode layer passes at a distance from the anode surface equal to several free path lengths of heavy plasma particles, beyond which the region of arc column begins, where a local thermodynamic equilibrium is established. In turn, the mentioned area can also be divided into two zones. The first of these zones is a layer of nonisothermal ionization equilibrium plasma, within which an equalization of the temperature of the electrons T_e and the temperature of the heavy particles T_h with the temperature in the arc column T occurs.

The other zone is actually an arc column (temperatures are measured in K). Moreover, the author of [9] assumes that the surface of the anode is flat and this fact allows him constructing a one-dimensional mathematical model of the anode layer of a high-current arc that burns in an inert gas medium of the atmospheric pressure. This statement is quite true if the welding current is $6\cdot10^2$ A or higher, but taking into account the fact that streamers formation occurs at very low currents and the breakdown voltage depends on the curvature of the electric field, the use of this statement is not possible. In [2] the author provides a generalized expression for the breakdown voltage U_{br} in most plasmatrons and torches for welding in an inert gas environment

$$U_{\mathrm{br}} = \left(K'_{1\,\mathrm{surf}} - K'_{2\,\mathrm{surf}}\frac{p}{p_0}\right)\left[1 - k\cdot\lg\frac{f}{f_{\mathrm{cr}}}\left(\frac{p}{p_0}\right)^{\frac{1}{3}}\right]\times$$
$$\times\left[1 + \left(\frac{\tau_0}{t_{\mathrm{p}}}\cdot\frac{p_0 h_o}{ph}\right)^{\frac{1}{3}}\right]U_{\mathrm{st}}, \qquad (8)$$

where $K'_{1\,\mathrm{surf}}$, $K'_{2\,\mathrm{surf}}$ and k are the coefficients, which depend on the surface finish of the electrode of the plasmatron or torch in an inert gas medium: coefficient τ_0 is the duration of the discharge delay at p_0h_0 also depends on the surface finish of the electrode of the plasmatron or torch $\tau_0 = \tau'_0 K^{-1}_{2\,\mathrm{surf}}$.

It should be noted that the coefficient $K^{-1}_{2\,\mathrm{surf}}$ can also be determined experimentally because of the fact, that the expression (8) requires a lot of experimental welding operations and is not very suitable for engineering calculations. It should also be noted that the solution of the problem of electrical breakdown is possible by building a one-dimensional or multidimensional model. The advantages of the one-dimensional problem of electric breakdown consist in the fact that such a model makes it possible to analyze formulas and graphs, but at the same time it does not guarantee a complete coincidence with the results of experiments.

The experience and numerous experiments convincingly prove that the calculated and actual values of breakdown voltage coincide with (8) by at most 50 % and depend on a number of factors, and therefore, to provide contact-free initial excitation of the welding arc, the developers of pulsed welding oscillators or electronic high-voltage pulsed generators are forced to use devices that generate pulses with an amplitude from 4.0 to 10.0 kV. Since the theory of a multidimensional model of electric breakdown does not yet exist, it is possible to assume that this model is more applicable for the analysis of the phenomena associated with repeated excitations at alternating welding current. In the case of direct welding current, a one-dimensional model is more applicable.

According to a number of authors [1–6, 8–10], the main gas-dynamic process in a spark discharge channel is its expansion under the action of a shock wave, which allows accepting homogeneous model of this discharge with a dense shell and a discharge plasma considered as thermodynamically equilibrium, which is characterized by a temperature T. Moreover, the pressure in the channel can be considered constant, equal to the pressure of the unexcited gas. The author of [2] also states that, in any case, this nature of the shock wave has a maximum current.

In [2], it is shown that the influence of the initial conditions on the conductivity of the interelectrode gap at the end of the spark discharge process, as well as the inductance of the discharging circuit (which mainly affects the initial stage of the process), is insignificant. The process of development of the spark channel ends at the moment when the voltage on the interelectrode gap becomes equal to the open-circuit voltage of the welding current source.

The formation of a current-conducting spark channel provides a sudden increase in the conductivity of the interelectrode gap, and if the welding power source connected to this gap, has a sufficient power, the electric spark can turn into a long nonstationary arc discharge with its inherent cathode and anode spots.

Having performed a number of experimental works, G.I. Leskov and V.P. Lugin came to the conclusions important for the construction of pulse devices designed for the initial contactless excitation of welding arc [11]. These researchers proved that other conditions being equal, the material of welding electrodes, the composition of their coating and the gas flow rates usual for welding have almost no effect on the value of the breakdown voltage. Also, no noticeable effect of the direction frequency (in the range from 100 to 3000 Hz) and the shape of high-voltage pulses entering the interelectrode gap were detected. It was established that the main factors determining the value of the breakdown voltage (i.e. the streamer formation) are the gas composition in the interelectrode gap, the length of this gap and the degree of inhomogeneity of the electric field. Moreover, the main molecular-kinetic characteristic of gas, on which the value of the breakdown voltage depends, is the Ramsauer cross-section of atoms or gas molecules.

Analysis of the results of [11] and experimental works of other researchers allowed obtaining empirical expressions for determining the approximate averaged values of the electric breakdown voltage (U_{br}) in some gaseous media of technologically motivated interelectrode gaps [12]. Regarding the duration of the delay, which occurs when electric breakdown voltage is applied to the interelectrode gap, this duration is determined mainly by the time interval before the appearance of the first electron, which can cause avalanche formation (streamer formation), i.e. the statistical interval of time delay, which depends on the concentration of molecules in the gas volume of this interval and on the excess of the voltage value over the value of the voltage of the electric breakdown in a static field. In real welding installations, the delay time usually does not exceed a few microseconds and the volt-second characteristic, i.e. the dependence of the breakdown voltage on the pulse duration applied to the interelectrode gap, can be determined according to the data of Cooper or Ritz or with the use of Paschen curves. When a probability of electric breakdown is 50 % for the conditions that exist in arc and plasma welding, according to [1], the volt-second characteristic can be calculated with a large approximation by the expression

$$U_{\text{br}} = \left(1 + \sqrt[3]{\frac{a}{t_{\text{p}}\,pd}}\right) U_{\text{br.st}}, \tag{9}$$

where α is a constant that depends on the type of gas in the interelectrode gap; t_{p} is the duration of the voltage pulse applied to the interelectrode gap C; $U_{\text{br.st}}$ is the voltage of electric breakdown in a homogeneous static field, V.

If at a set value *d* (length of the interelectrode gap) the energy W_{p} of the voltage pulse applied to it is sufficient, then immediately after the electric breakdown of the gap, a spark discharge occurs, which, as established in VNIIESO [1], the initial stage of the spark discharge is accompanied by a significant increase in the conductivity of the interelectrode gap, and in the final stage of the spark discharge — by its drop [1, 2]. Depending on the conditions in the interelectrode gap and the properties of the welding power source connected to it, upon completion of the spark discharge, either complete attenuation of this discharge or the occurrence of a glowing or arc discharge is possible. The studies showed [1] that the arc in the interelectrode gap arises only in the case, when the resistance R_{c} of the conductive channel formed by the spark discharge is less than some threshold value R_{thr}, which depends on the current input rate of the welding power source in the channel, the arc time constant, the voltage in the interval *u*(*t*) and other factors. For a DC welding arc, the approximate value R_{thr} can be determined by the expression:

$$R_{\text{thr}} \approx \left(\frac{n\theta \left.\dfrac{di}{dt}\right|_{t=0} U_{\text{o.-c}}^{\frac{n+3}{n-1}} a^{\frac{n+1}{n-1}}}{2 + n\theta \left.\dfrac{di}{dt}\right|_{t=0} U_{\text{o.-c}}^{\frac{n+1}{n-1}} a^{\frac{n}{n-1}}} \right)^{n}, \tag{10}$$

where *n* is the value of the approximation degree; θ is the arc time constant, s; *di*/*dt* is the rate of increase in the arc supply current at the initial moment (at $t = 0$), A/s; $U_{\text{o.-c}} = u(0)$ is the open-circuit voltage of the welding power source, V.

Fulfilment of the condition $R_{\text{c}} < R_{\text{thr}}$ depends not only on the level of U_{thr}, but also on the level of power of the voltage pulses, which cause a spark discharge in the interelectrode gap. Since the duration of these pulses is determined by the reactive parameters and the quality factor of the forming circuits of the generators of overvoltage pulses (GVP) of the boosting devices and the power source circuits of the arc, it is much more convenient to operate with such a parameter of pulses as their energy W_{p} (in J). Also, since in the vast majority of cases during the formation of pulses produced by GVP, the energy of preliminary charged capacitive storages is consumed, it can be assumed that $W_{\text{p}} = CU_{\text{c}}^2/2$, where *C* is the capacitance of the capacitor (capacitors), F; U_{c} is the constant charge voltage of the capacitance, V. In [12] the values of W_{p} are given, which are recommended for different gaseous media and technologically motivated interelectrode gaps and obtained experimentally and confirmed by the experience in designing and application of electronic boosting devices.

The streamers formation also depends on the cathode phenomena [1, 4, 8], but it should be noted that their theory is not fully developed, as well as the theory of the AC arc excitation.

Because of a high mobility of electrons, an uncompensated bulk charge is formed near the cathode, due to which a cathode drop of the U_{c} potential exists. Moreover, near the cathode, there is an area of transition from the arc column to the narrowed area — such that is subjected to contraction — cathode region [1]. Here the electric field strength is much higher than in the arc column. In the area of the cathode potential drop, electrons and positive ions undergo acceleration, due to which electrons can carry out shock ionization, and ions can carry a much larger fraction of current as compared to the column plasma [1].

The energy obtained by the cathode from ions that bring their neutralization energy and kinetic energy of movement and which comes from the plasma of the column (due to thermal conductivity and radiation), is spent on compensating the electron output, thermal conductivity and cathode radiation, on its melting and evaporation and on the dissociation of molecular gases [1, 4, 8]. The share of all these components is different and depends on the conditions in which the arc burns. Among these conditions, the main role belongs to the cathode material [1]. There are two types of cathodes: «non-fusible» or hot cathodes of tungsten or carbon, and «fusible» or cold electrodes of low-melting materials. On refractory cathodes, which are mainly used in arc and plasma welding, a stationary spot is formed, which radiates quite strongly. At the same time with an increase in temperature of the cathode to some critical value, the spot by a jump disappears, and narrowing of the column near the cathode is absent [1].

The volt-ampere dependence of the near-cathode region of the arc column at low currents is falling [1, 2, 4, 8, 9].

The temperature of the cathode is close to the melting point of the welded metal, and the current densities per cathode, which are measured by the spot area, range from 10^9 A/m^2 in the arcs with a spot to 10^7 A/m^2 in the arcs without a spot A/m^2. Since the theory that explains all the factual material regarding cathode phenomena is still absent, the theory of thermoelectron arc, according to which the current from the cathode is provided by thermoelectrons and ions.

The density of thermoelectric current is determined by the Richardson–Dushman formula or by the formula, that takes into account the distortion of the potential barrier. The energy required to create thermoelectrons is supplied to the cathode by ions, and in this case the fraction of ionic current J_p is

$$\frac{J_p}{J} = \frac{U_{out}}{U_c + U_{neut}}. \qquad (11)$$

For different conditions, this value ranges from 0.15 to 0.35, and at lower values of the fraction of ionic current, in order to explain the required heating of the cathode, the heat transfer from the plasma should be taken into account [1].

It should be noted that thermoelectronic theory is not able to explain the phenomena at the cathode of low-melting materials, because in this case to form a spatial charge the current density at the cathode should be at least 10^{11}A/m^2. Taking into account the presence of thermoelectrons, this value decreases to the actual value of 10^9 A/m^2. According to the autoelectronic theory $J_p << i_e$, the current is transferred by electrons, which carry out step ionization in the zone of a cathode potential drop.

When calculating the autoelectronic current density, in addition to taking into account the presence of a dielectric film on the cathode surface, the presence of microroughnesses on its surface should also be taken into account, due to which the effective field strength can be several times increased [1]. But, despite these specifications, the autoelectronic theory is also not able to explain the whole set of processes at the cold cathode.

As far as for arc and plasma welding, alternating current mainly of industrial frequency and the frequencies close to it is used (from 50 to 400 Hz), there is every reason to believe that the condition $R_c < R_{thr}$ is valid in the case of alternating current, here R_{thr} is also determined by the expression (10), which determines the requirements characteristic of alternating current until the start of the generation of pulses, exciting the welding arc.

The excitation of the arc discharge largely depends on the value of the voltage applied to the interelectrode gap. Therefore, the pulse that excites the welding arc should begin to be injected into the interelectrode gap near the maximum of this voltage (near the amplitude of the open-circuit voltage of the welding source). Numerous investigations found that in the sinusoidal waveform arc current, the phase of the beginning of generating the pulse, exciting the arc, should be (75–80) electr. deg. relative to the zero phase of the open-circuit voltage of the welding power source, while the condition of a sufficiently high rate of increase in the arc discharge current should be met. The highest efficiency of the initial excitation of the AC arc is achieved when the phase of the beginning of the generation of the pulse exciting the welding arc coincides with the moment of transition of the constant welding current of the arc through the zero value. In addition, electrophysical conditions of emission from the electrodes are important for contactless initial excitation of the arc, which can be very different for the AC arc depending on the electrode material and the fact, whether the electrode is an anode or cathode at the moment of the initial arc excitation. This is especially characteristic of TIG welding of aluminium and its alloys, in which the initial excitation of the arc almost always occurs during the time intervals, when the cathode is a product to be welded. It seems that this can be explained by the fact, that during excitation of the welding arc, nonconsumable (tungsten) electrode is characterized by thermoemission, the formation of which is associated with the need of heating the electrode to the emission temperature, and this process is inertial. At the same time, at a cathode formation on a welded product of aluminium and its alloys (especially if the outer surface of a product is covered with an oxide film Al_2O_3) an almost noninertial autoelectron emission occurs [1, 2, 10, 13].

The problems of stability of the AC welding arc attracted attention over the past century and continue to attract the attention of researchers and specialists in the field of electrical technologies and in the field of electrical engineering. As a result of many years of extensive theoretical and experimental investigations, generalized, for example, in [1, 9–15], a considerable experience has been accumulated, which allows explaining a number of phenomena and features of the AC arc, as well as formulating the main conditions of constancy of the arc discharge, including application of analytical methods.

The AC welding arc periodically changes its polarity and, as a result, the same electrode alternately is either the cathode or the anode. The change in the polarity of the electrodes causes changes in the intensity and direction of gas flows in the arc and reorientation of charged particles in its column. It was established that the processes in the arc column have a decisive influence on the behaviour of the welding arc and its characteristics during almost the entire duration of each half-cycle of alternating current, except for short intervals near the current transition through zero, during which the arc discharge is absent and at best, it is glowing in the residual plasma [1, 5, 7, 9, 10, 12–15].

The presence of pauses in the existence of the arc discharge in the interelectrode gap near the current transition through the zero value is the main characteristic feature of the AC welding arc, at the end of each half-period of which before and after the arc discharge attenuation, the gas temperature in the arc decreases significantly and accordingly, the conductivity of the interelectrode gap is significantly reduced and at the same time the temperature of the anode and cathode spots drops [1, 9, 10, 12–14].

This and other features of the AC welding arc are considered in detail in the works [1, 4, 10, 12].

Conclusions

1. For better explanation of the whole set of processes associated with the initial and repeated excitations of the welding arc, including alternating current arc, as well as to develop engineering procedures for calculating the combined devices-exciters-stabilizers, the further theoretical and experimental investigations, especially in the direction of studying near-cathode phenomena are required.

2. As a result of consideration and generalization of features of contactless initial and repeated excitations of welding arc performed on the basis of the use of the known literary sources, theoretical and experimental works of different authors and available experience of development and application of means of realization of these processes, it was established that in the mode of initial excitation (ignition) of the arc depending on the conditions in the interelectrode gap (its length, type and pressure of gas in it, the shape and purity of the working end of the welding electrode and a product to be welded, the basic parameters of the output high-voltage pulses, which are generated by the combined exciters-stabilizers, should have the following values: pulse energy — from 0.01 to 0.50 J, pulse amplitude — from 3.5 to 10.0 kV, duration (at the level of 0.05 of amplitude value) — from 3 to 20 μs.

It was also established that in the mode of stabilization of the AC welding arc (i.e. at repeated excitations) depending on the degree of deionization and the associated decrease in the conductivity of the interelectrode gap at each change in the polarity of the arc current, the basic parameters of the output high-voltage pulses generated by combined exciters-stabilizers, should be: pulse energy — from 0.2 to 1.0 J, pulse amplitude — from 400 to 950 V, duration (at the level of 0.05 amplitude value) — from 50 to 100 μs, and in some cases (for example, during welding with a fusible electrode in the CO_2 environment) — from 0.2 to 1.0 ms.

3. To solve the problem of determining the required parameters of the pulses of the initial and repeated excitations of the welding arc, both one-dimensional as well as multidimensional models can be used (however, the theory of a multidimensional model still does not exist). To solve the problem of determining the optimal parameters of the pulses of the initial excitation of the DC arc, one-dimensional model is the most applicable and common, which provides the ability to analyze formulas and graphs, but does not guarantee a complete coincidence with the experiments. When solving the problems of repeated excitations of the AC welding arc, multidimensional model can also find applicability (despite the absence of a complete theory). In this case, it becomes necessary to introduce a correction coefficient K_C for each parameter, which is equal to the ratio at each point of the experimental value. In the future, everything depends on the results of the obtained experimental correction curves.

4. Creation of combined exciters-stabilizers is possible only under the condition if their construction involves a series connection of the output circuits of these devices in the circuit of the welding or auxiliary (pilot) arc.

1. (1986) *Equipment for arc welding*: Refer. Book. Ed. by V.V. Smirnov. Leningrad, Energoatomizdat [in Russian].
2. Temkin, B.Ya. (1981) *Theory and calculation of welding arc exciters*: Syn. of Thesis for Cand. of Tech. Sci. Degree. Leningrad [in Russian].
3. Rajzer, Yu.P. (1987) *Physics of gas discharge*. Moscow, Nauka [in Russian].
4. Gvozdetsky, V.S. (1969) To the theory of cathode processes in electric arc. *Avtomatich. Svarka*, **1** (Pt 1), 33–37; **6**, (Pt 2), 1–4 [in Russian].
5. (1980) *Electrotechnical reference book*. In: 3 Vol., Vol. 1: General problems. Electrotechnical materials. Ed. by V.G. Gerasimov, P.G. Grudinsky, L.A. Zhukova, et al. 6st Ed. Moscow, Energiya [in Russian].
6. Paton, B.E., Zaruba, I.I., Dymenko, V.V., Shatan, A.F. (2007) *Welding power sources with pulsed stabilization of arc burning*. Kiev, Ekotekhnologiya [in Russian].
7. Farson, D., Courardy, C., Talkington, J.et al. (1998) Arc initiation in gas metal arc welding. *Welding Res. Supl.*, **8**, 315–321.
8. Kesaev, I.G. (1968) *Cathode processes in welding arcs*. Moscow, Nauka [in Russian].
9. Krivtsun, I.V. (2018) Anode processes in welding arcs. *The Paton Welding J*., **11–12**, 91–104.
10. Leskov, G.I. (1970) *Electric welding arc*. Moscow, Mashinostroenie [in Russian].
11. Leskov, G.I., Lugin, V.P. (1971) Investigation of voltage breakdown of gaps between welding electrodes. *Svarochn. Proizvodstvo*, **2**, 10–11 [in Russian].
12. Makhlin, N.M. (2015) Peculiarities of contactless ignitions of alternating current arc. *The Paton Welding J.*, **10**, 29–35.
13. Weinshehk, H.E., Schellhase, M. (1971) Wiederzundugscharacteristiken von Schweißlichtbogen mit abschmelzen der Elektrode. *ZIS-Mitt*., 13**(12)**, 1706–1720.
14. Korotynskyi, O.E. (2007) *High-efficient power sources for arc welding on the base of inductive-capacitive transducers*: Syn. of Thesis for Dr. of Tech. Sci. Degree. Kyiv [in Ukrainian].
15. Pokhodnya, I.K. (1967) *Electrode melting and interaction of metal with gases in arc welding*: Syn. of Thesis for Dr. of Tech. Sci. Degree. Kiev [in Russian].

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