ON THE INFLUENCE OF CAPACITANCE IN THE WELDING CIRCUIT ON STABILITY OF ARC WELDING MODE

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Profound study of the influence of various kinds of destabilizing factors on welding process stability is one of the main tasks in its robotization. The influence of capacitance («parasitic» or purposefully included into the welding circuit) on stability of the mode of consumable-electrode gas-shielded arc welding was studied in this work. It is shown that at high and medium welding currents, i.e. when the working point is located in the rising or flat section of the arc volt-ampere characteristic, presence of a capacitance in the welding circuit does not affect the stability of steady-state arc welding mode. Now, in the case of small currents, when the working point is located in the falling section of this characteristic, ensuring the arc welding mode stability is possible only at limited values of the above capacitance. Established criteria in the form of algebraic inequalities allow comparatively simple evaluation of the region of this capacitance values, within which stable modes are guaranteed. Results presented in this paper will be useful in development of robotic welding technologies and respective process equipment. 17 Ref., 5 Figures.

Keywords: *robotic arc welding, consumable electrode, capacitance, steady-state modes, stability, transient processes*

The recently published paper [1] deals with the influence of capacitance on processes running in the electric arc powered from a direct current source. To study these processes, the authors used a circuit of a two-pole element substitution for an electric arc, including the arc differential resistance and small stray inductance connected in parallel with it, which is shunted by ohmic resistance, and a capacitance is connected in parallel to a two-pole element.

A similar problem was considered in a somewhat different aspect in the fundamental work «Theory of vibrations» [2]. Stability of steady-state modes in an electric circuit with an arc, connected in series with an inductance and shunted by a capacitance, was studied in it as an example (Figure 1). Now, the arc proper was regarded as a certain electric circuit element, static volt-ampere characteristic (VAC) of which reflects the main properties of the arc, and is known [3–10] to be essential for selection of the method of its powering and stabilizing.

In [2] conditions of asymptotic stability of steady-state modes were obtained in the form of the following inequalities:

$$R + S_a > 0, \quad L + S_aRC > 0, \qquad (1)$$

where $S_a = du_a/di$ is the tangent of the angle of inclination of arc VAC (arc differential resistance) in the vicinity of a point, corresponding to steady-state mode, and the meaning of other designations is clear from Figure 1. It is seen directly from expressions (1) that if $S_a \geq 0$, then both the inequalities will be fulfilled and, therefore, the steady-state mode will be asymptotically stable at any values of capacitance C. Now, if $S_a < 0$ (falling section of arc VAC), the steady-state mode will be asymptotically stable only up to those circuit parameter values, which satisfy the following conditions:

$$R > |S_a|, \quad C < \frac{L}{R|S_a|}. \qquad (2)$$

The first inequality in (2) is called Kauffman criterion [3, 8]; it is more often expressed as $|\partial u_R/\partial i| > |\partial u_a/\partial i|$, where u_R is the potential drop across resistance R.

Results obtained in [2] pertain to the case, when electric arc length during its arcing remains unchanged (voltaic arc). The question naturally arises: what is the influence of capacitance C on stability of the processes running in the real weld-

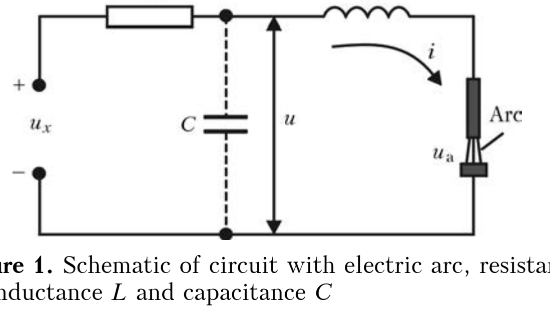

Figure 1. Schematic of circuit with electric arc, resistance R, inductance L and capacitance C

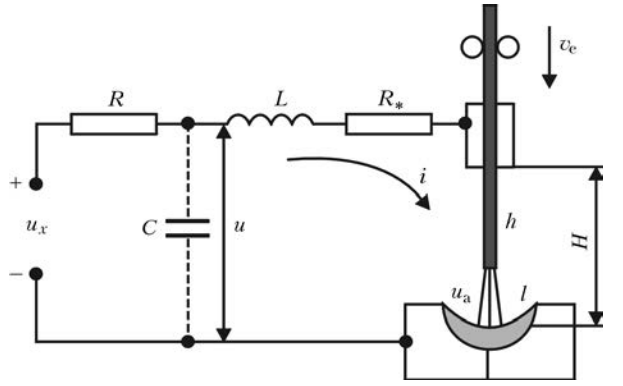

Figure 2. Schematic of welding circuit with consumable electrode and capacitance

ing circuit in consumable-electrode gas-shielded arc welding, when the arc length is a variable value in principle? Judging by the known publications (see, for instance [3–12] and references given there), this still remained insufficiently studied. Considering that consumable-electrode gas-shielded arc welding is one of the predominant welding technologies, the posed question is of practical interest and in our opinion it deserves a more detailed study.

Let us consider the schematic of the welding circuit, shown in Figure 2. It differs from the circuit in Figure 1 by that it uses a consumable electrode, which is fed into the welding zone at certain rate v_e. Electrode feed rate v_e = const and its melting rate $v_m = v_m(t)$ at an arbitrary moment of time t are connected to current value of electrode extension $h = h(t)$ by the following relationship:

$$h = h_0 + v_e t - \int_0^t v_m(t)dt, \tag{3}$$

where h_0 is the initial value of electrode extension. Electrode melting rate, in its turn, depends on welding current $i = i(t)$ and on thermophysical and geometrical properties of the electrode. This dependence is often approximated by linear function [5, 6, 13]

$$v_m = Mi, \tag{4}$$

where M is the parameter, characterizing the above properties.

Distance H between the edge of current-conducting nozzle and weld pool free surface in robotic arc welding is maintained constant. This distance, as is seen from the circuit, is equal to a sum of current values of arc length $l = l(t)$ and electrode extension $h = h(t)$, i.e.

$$H = l + h = \text{const}. \tag{5}$$

We will complement relationships (3)–(5) by the following dependence [12, 13]:

$$u_a = u_0 + El + S_a i \tag{6}$$

and differential equations

$$L\frac{di}{dt} + R_* i = u - u_a, \quad C\frac{du}{dt} = \frac{u_x - u}{R} - i, \tag{7}$$

composed on the basis of the considered circuit and Kirchhoff's laws.

In equations (6) and (7) u_a is the arc voltage; u_0 is the sum of near-electrode voltage drops; $E = du_a/dl$ is the electric field intensity in the arc column; R_* is the total resistance of current-conducting wires, electrode extension and sliding contact in welding torch nozzle.

Excluding i, h, v_m, u, u_a variables from the system of equations (3)–(7), we will obtain one differential equation for variable l:

$$CL\frac{d^3l}{dt^3} + \left(\mu CR + \frac{L}{R}\right)\frac{d^2l}{dt^2} + (1 + \mu + CEM)\frac{dl}{dt} + \frac{EM}{R}l = \frac{M}{R}(u_x - u_0) - (1 + \mu)v_e. \tag{8}$$

All the dimensional parameters, appearing in this equation, are positive. Dimensionless parameter μ, equal to

$$\mu = \frac{R_* + S_a}{R}, \tag{9}$$

can take both a positive, and a negative value, depending on S_a sign and the relationship between $|S_a|$ and R_* in the vicinity of working point. Furtheron we will assume that $|\mu| < 1$. Steady-state value of arc length $l_\infty = \lim_{l \to \infty} l(t)$, i.e. its value at

$$\frac{d^3l}{dt^3} = 0, \quad \frac{d^2l}{dt^2} = 0, \quad \frac{dl}{dt} = 0$$

is determined according to (8) by the following expression:

$$l_\infty = \frac{u_x - u_0}{E} - \frac{R(1 + \mu)}{EM}v_e, \tag{10}$$

which, as we can see, does not include capacitance C.

Now, let us consider the influence of this capacitance on arc welding mode stability. We will introduce variable $\lambda = l - l_\infty$. Allowing for this variable and expressions (8) and (10), we obtain the following equation:

$$CL\frac{d^3\lambda}{dt^3} + \left(\mu CR + \frac{L}{R}\right)\frac{d^2\lambda}{dt^2} + (1 + \mu + CEM)\frac{d\lambda}{dt} + \frac{EM}{R}\lambda = 0, \tag{11}$$

describing the transient process in the welding circuit.

From this equation it is immediately evident that if the following conditions are fulfilled:

$$\mu CR^2 + L > 0, \quad 1 + \mu + CEM > 0, \\ \mu R^2 EMC^2 + \mu R^2(1 + \mu)C + L(1 + \mu) > 0, \tag{12}$$

then according to Hurwitz criterion [14] the steady-state mode will be asymptotically stable in the considered circuit.

Let us separately consider three special cases.

1st: $S_a \leq 0$. i.e. the arc VAC rises or remains unchanged in working point vicinity (arc welding at large and medium currents). In this case, $\mu > 0$ according to (9). It is easy to see that here all the three conditions of stability (12) are satisfied at any values of capacitance C;

2nd: $S_a < 0$ and, in addition, $|S_a| \leq R_*$. This corresponds to falling section of arc VAC (small current welding) and the case, when arc differential resistance S_a by its absolute value is smaller or equal to total resistance of current-conducting wires, electrode extension and sliding contact in welding torch nozzle. In this case, $\mu \geq 0$. Therefore, now also all the three conditions of stability are fulfilled at any values of capacitance C (12);

3rd: $S_a < 0$, but at the same time $|S_a| > R_*$. In this case, according to (9) $\mu < 0$, and it means that the steady-state mode (10) will be stable, only when the following conditions are fulfilled according to (12):

$$C < \frac{L}{|\mu|R^2}, \quad 1 + CEM > |\mu|, \\ \frac{EM}{(1 - |\mu|)}C^2 + C < \frac{L}{|\mu|R^2}. \tag{13}$$

Considering these conditions, it is easy to see that at $|\mu| < 1$ the second condition is always fulfilled. If the third condition is fulfilled here, the first condition is sure to be fulfilled, too. Now, the third condition proper is an algebraic inequality of the second kind for C. Its solution has the following form:

$$C < -a + \sqrt{a^2 + 2ab}, \tag{14}$$

where

$$a = \frac{1 - |\mu|}{2EM}, \quad b = \frac{L}{|\mu|R^2}. \tag{15}$$

Inequality (14) yields the region of possible values of capacitance C, which guarantee the stability of arc welding mode, described by equation (8) at $\mu < 0$. In some cases, for instance at express-analysis of stability, it is more convenient to use a simpler relationship, instead of (14):

$$C < \sqrt{ab}, \tag{16}$$

which at $b > 4a$ also satisfies the third inequality from (13), but limits a somewhat smaller region of values of capacitance C, compared to «precise» region determined by relationship (14). Note that condition $b > 4a$ can be ensured by selection of the required R value in formulas (15), which actually determines the steepness of VAC of welding arc power source in the considered working point $R = |du/di|$.

So, in welding at small currents, when arc VAC has a falling section, and here $|S_a| > R_*$, condition (14) and two simpler $C < \sqrt{ab}$ and $b > 4a$ conditions should be fulfilled in addition to condition $|\mu| < 1$, to ensure the stability of arc welding mode. In the latter case, conditions of stability, allowing for (15) and (16), can be written in the following final form:

$$|\mu| < 1, \quad \frac{LEM}{2|\mu|}, \quad C^2 < \frac{L(1 - |\mu|)}{2R^2|\mu|EM}. \tag{17}$$

The first condition from (17) at $R_* = 0$ is reduced, according to (9), to Kauffman criterion $|S_a| < R$, i.e. it is a certain refinement of this criterion. The second condition assigns the upper limit of possible angles of inclination of arc power source VAC at already selected other parameters of the welding circuit. The third condition limits the value of capacitance C from the top. Conditions of stability (17), unlike conditions (2), connect not only parameters C, L, R, S_a, but also parameters R_*, M and E, characterizing the electrical, thermophysical and geometrical properties of the consumable electrode and electric field intensity in the arc column.

It should be noted, however, that fulfillment of conditions (17) ensures just the fundamental possibility of the system reaching the steady state after a small external disturbance, but it does not guarantee absence of negative influence of capacitance C on the nature of transient processes in the welding circuit. To obtain the most complete idea of the extent of the above influence, let us use computer simulation of arc welding process. We will focus on small welding current modes, in the region of which, as is known [3–6, 8], the arc characteristic is falling. These are exactly the modes, in which, according to (17), an essential influence of capacitance C on the transient processes should be anticipated.

During simulation we will use typical values of mode parameters of robotic arc welding at small currents [15], namely $u_x = 30$ V, $i = 40$ A, $v_e = 25$ mm/s, $H = 15$ mm, and real parameters of welding circuit $R = 6\cdot10^{-2}$ Ohm, $R_* = 1\cdot10^{-2}$ Ohm,

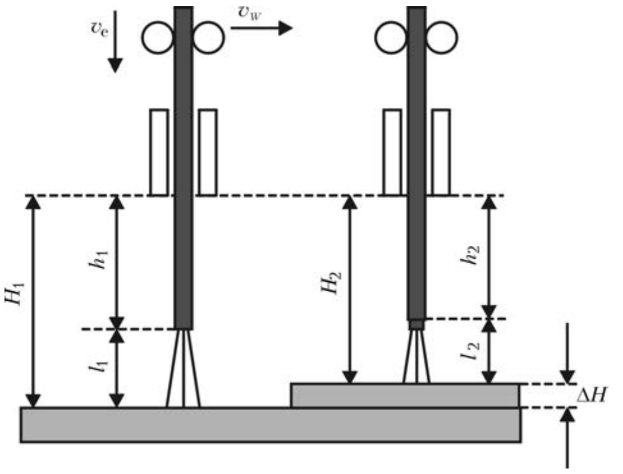

Figure 3. Schematic of realization of jump-like disturbance ΔH

$L = 1\cdot10^{-3}$ H, $E = 2$ V/mm, $u_0 = 18$ V, $M = 0.5$ mm/(s·A). As regards arc differential resistance S_a, we will take the value from the graph of VAC given in [6], because of the known difficulties of its direct measurement: in small current region (i = 20–60 A) it is equal to $S_a \approx -1.5\cdot10^{-2}$ V/A.

Assigning the range of possible values of capacitance C during modeling, we will proceed from the following considerations. Any electric circuit contains the so-called «parasitic» capacitance. Its minimum value for the welding circuit, according to [6], is equal to $C_m \approx 1\cdot10^{-8}$ F. At the same time, it is known [1] that capacitance can be specially added to the welding circuit. In such a case, it is desirable to determine the upper limit of this capacitance values, above which the transient process becomes unsatisfactory in terms of technical requirements to consumable-electrode arc welding.

As disturbing action, giving rise to transient process (11) in the welding circuit, we will use, as shown in Figure 3, the jump-like variation of distance $\Delta H = H_2 - H_1$ between the edge of current-conducting tip and weld pool free surface. Figures 4 and 5 show the results of computer simulation.

Figure 4, *a* presents three graphs $l = l(t)$, showing the reaction of arc length $l(t)$ to disturbance $\Delta H = -3$ mm at $S_a = -1.5\cdot10^{-2}$ V/A and at different values of capacitance C. Curve *1* is the graph of several transient processes, which practically coincide, although the capacitance values, at which these graphs were derived, fall within a broad range $0 < C \leq 0.1$ F. Hence, it follows that until capacitance C does not exceed a certain value (in our case, 0.1 F), its influence on the transient process is negligibly small. Only at further increase of this capacitance, the shape of transient process curves changes noticeably (curves *2* and *3*), acquiring an oscillatory nature, with oscillation amplitude rising with capacitance increase.

Figure 4, *b* shows graphs $l = l(t)$ plotted at the same values of capacitance C as the graphs in Figure 4, *a*. However, unlike these, the graphs in Figure 4, *b* were plotted at condition $S_a > 0$. Comparing these graphs, we come to the conclusion that in the case when $S_a < 0$, influence of capacitance C on transient processes in the weld-

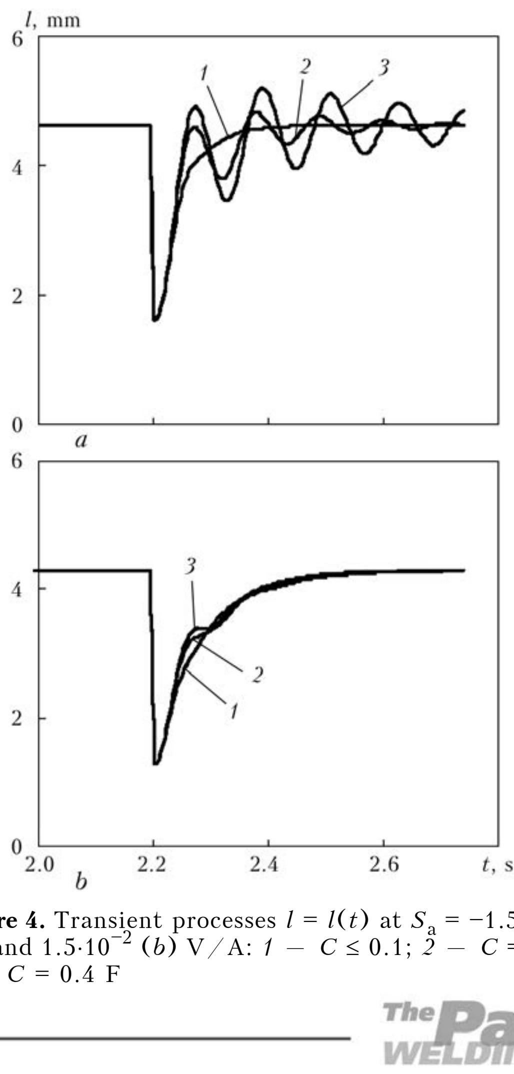

Figure 4. Transient processes $l = l(t)$ at $S_a = -1.5\cdot10^{-2}$ (*a*) and $1.5\cdot10^{-2}$ (*b*) V/A: *1* — $C \leq 0.1$; *2* — $C = 0.3$; *3* — $C = 0.4$ F

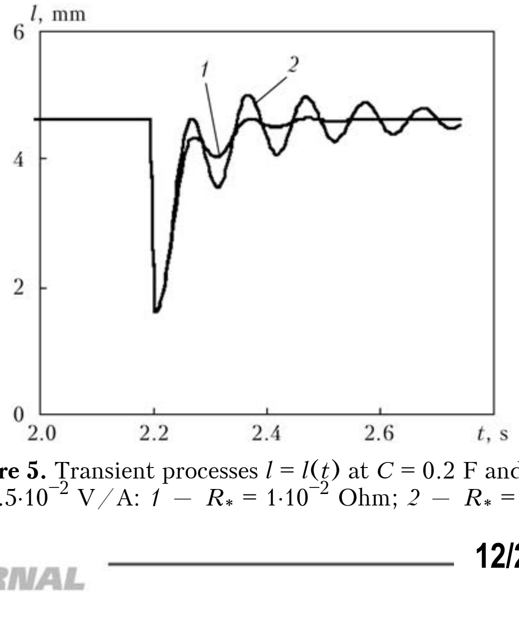

Figure 5. Transient processes $l = l(t)$ at $C = 0.2$ F and $S_a = -1.5\cdot10^{-2}$ V/A: *1* — $R_* = 1\cdot10^{-2}$ Ohm; *2* — $R_* = 0$

ing circuit is much higher than in the case when $S_a > 0$.

Note one more important circumstance. To get an adequate insight into the transient processes running in the welding circuit at $S_a < 0$, it is necessary to take into account total resistance R_*, alongside its other parameters. This impedance is usually ignored, being considered negligibly small. In reality, as to its order of magnitude, it is commensurate with absolute value of the arc differential resistance S_a. Therefore, its influence on the transient process in the welding circuit can turn out to be quite tangible.

Results, given in Figure 5, are an illustration to the above-said. It presents $l = l(t)$ graphs, plotted at two different values of resistance R_*. Curve *1* is the reaction of arc length $l(t)$ to disturbance $\Delta H = -3$ mm, when $R_* = 1 \cdot 10^{-2}$ Ohm, and curve *2* is the same at $R_* = 0$. It is readily seen from the Figure that these curves differ considerably from each other. This immediately implies that ignoring resistance R_*, we certainly obtain incorrect information about the transient processes, running in the welding circuit.

The above-said leads to the following conclusions.

1. At high and medium welding currents, when the working point is located in the rising or flat section of the arc VAC, presence of capacitance in the welding circuit does not affect the stability of arc welding mode. Capacitance C does not influence the stability in the case of small currents, either, when the working point is located in the falling section of this characteristic, but only if the arc differential resistance S_a is smaller by absolute value than the total resistance of current-conducting wires, electrode extension and sliding contact in welding torch nozzle, i.e. if $|S_a| < R_*$.

2. In the case when $|S_a| > R^*$, presence of sufficiently large capacitance in the welding circuit can lead to loss of stability of arc welding mode. Established criteria in the form of algebraic inequalities (17) allow evaluation of upper limit of the region of this capacitance values, within which stable welding modes are guaranteed.

3. Results of computer modeling of processes running in the welding circuit show that small capacitance (of the order of hundredth of a farad) does not have any noticeable influence on transient processes in arc welding, either at small or at high currents. Further increase of this capacitance in welding at small currents leads to generation of noticeable oscillations of arc length, which increase as the capacitance approaches the limit of stability, determined by conditions (17). The given modeling results confirm one more important finding that in order to obtain an adequate insight into the transient processes running in the welding circuit, it is necessary to take into account the real resistances of current-conducting wires, electrode extension and sliding contact in welding torch nozzle.

In conclusion we will note that recently specialists' attention was focused on solving one of the difficult problems, associated with robotisation of arc welding of thin-walled items and structures [16, 17]. It is obvious that their welding should be performed at small and very small welding currents. In this connection, the results set forth in this paper, will be useful in development of robotic welding technologies and respective process equipment.

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