EVALUATION OF QUALITY OF THE ARC SELF-ADJUSTMENT PROCESS

G.A. TSYBULKIN
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Steady-state modes in the welding circuit during gas metal arc welding are considered. An approach is offered to evaluate quality of the arc self-adjustment process based on the use of the error index method.

Keywords: *arc welding, consumable electrode, transient- and steady-state process, accuracy of self-adjustment*

Efficiency of control algorithms for robotic metal arc welding significantly depends on how the character of dynamic processes taking place in the welding circuit is allowed for during their development. The peculiarity of these processes is determined by the effect of self-adjustment of the arc, which, as is well known, was discovered and thoroughly investigated as far back as in the early 1940s [1]. Though there are lots of studies dedicated to investigation of the above effect, the issues of quality of the arc self-adjustment process are yet insufficiently covered in literature. We can mention only the recently published paper [2], which uses an integral performance criterion, allowing comparison of the systems close in structure (the best of them has the lowest integral estimate). The paper [2] does not consider the issues of accuracy in the steady-state modes, which, along with the transient process time, is known [3–7] to be one of the main indicators of the process quality.

Meanwhile, a smart method, described probably for the first time in study [7] and later known as an error index method, was suggested for analysis of accuracy in steady-state modes under conditions of constant, slowly varying external actions. This method makes it possible to quite easily obtain an idea of the steady-state processes in linear feedback systems of a random structure directly from coefficients of the transfer functions depending on the external actions and their derivatives. It is shown in study [8] that the above method, in principle, also applies to certain classes of non-linear systems, in which the non-linear elements are not connected by feedback circuit.

The task of this study is to investigate the steady-state process in the welding circuit during gas metal arc welding, and estimate accuracy of the arc self-adjustment process based on the error index method.

Consider the following differential equation:

$$(T_eT_sD^2 + T_sD + 1)v_m = v_e - DH + \frac{1}{E}Du_s, \qquad (1)$$

which describes, according to [9], the dynamic processes taking place in the welding circuit.

The following designations are introduced in equation (1): $v_e = v_e(t)$ — consumable electrode feed speed relatively to the torch nozzle; $v_m = v_m(t)$ — electrode melting rate; $H = H(t)$ — distance between the tip of the current-conducting nozzle and free surface of the weld pool; $u_s = u_s(t)$ — voltage at output terminals of the welding current source; $E \equiv \partial u_a/\partial l$ — intensity of the electric field in the arc column; $u_a = u_a(t)$ — arc voltage; l — arc length; t — current time; $D = d/dt$ — differentiation operator; and T_e, T_s — time constants:

$$T_e = \frac{L}{R_*};\ \ T_s = \frac{R_*}{EM}. \qquad (2)$$

Here L is the inductance of the welding circuit; $M \equiv \partial v_m/\partial i$ is the slope of the electrode melting characteristic at nominal values of the welding current i; and electrode extension

$$R_* = R + S_a - S_s, \qquad (3)$$

where R is the total resistance of the lead wires, electrode extension and sliding contact in the torch nozzle; $S_a \equiv \partial u_a/\partial i$; $S_s \equiv \partial u_s/\partial i$ is the slope of volt-ampere characteristics of the arc and welding current source at a nominal value of the welding current i.

Assume the following value to be a criterion of accuracy of self-adjustment:

$$\varepsilon(t) = v_e(t) - v_m(t), \qquad (4)$$

which is a deviation of electrode melting rate $v_m(t)$ from electrode feed speed $v_e(t)$.

Based on (4) and (1), it can be written down that

$$(T_eT_sD^2 + T_sD + 1)\varepsilon(t) = \\ = (T_eT_sD^2 + T_sD)v_e(t) + DH(t) - \frac{1}{E}Du_s(t). \qquad (5)$$

Applying the Laplace transformation to (5), we obtain

$$\varepsilon(p) = W_1(p)v_e(p) + W_2(p)H(p) - W_3(p)u_s(p), \qquad (6)$$

where p is the complex variable; and $W_1(p)$, $W_2(p)$ and $W_3(p)$ are the transfer functions:

$$W_1(p) = \frac{T_eT_sp^2 + T_sp}{T_eT_sp^2 + T_sp + 1}; \quad W_2(p) = \frac{p}{T_eT_sp^2 + T_sp + 1};$$

$$W_3(p) = \frac{E^{-1}p}{T_eT_sp^2 + T_sp + 1}. \tag{7}$$

Since transfer functions $W_1(p)$, $W_2(p)$ and $W_3(p)$ have no poles at the origin of coordinates, then, according to [7], they can be expanded into power series with regard to p. Therefore, steady-state deviation $\varepsilon_\infty(t)$ for each input action $v_e(t)$, $H(t)$ and $u_s(t)$ can be represented as a sum of corresponding expansions

$$\varepsilon_\infty(t) = \varepsilon_{1\infty}(t) + \varepsilon_{2\infty}(t) + \varepsilon_{3\infty}(t), \tag{8}$$

where

$$\begin{aligned} \varepsilon_{1\infty}(t) &= A_0v_e(t) + A_1Dv_e(t) + A_2D^2v_e(t) + \ldots; \\ \varepsilon_{2\infty}(t) &= B_0H(t) + B_1DH(t) + B_2D^2H(t) + \ldots; \\ \varepsilon_{3\infty}(t) &= C_0u_s(t) + C_1Du_s(t) + C_2D^2u_s(t) + \ldots \end{aligned} \tag{9}$$

In these expressions

$$A_n = \frac{1}{n!}\left[\frac{d^nW_1}{dp^n}\right]_{p=0}; \quad B_n = \frac{1}{n!}\left[\frac{d^nW_2}{dp^n}\right]_{p=0};$$

$$C_n = \frac{1}{n!}\left[\frac{d^nW_3}{dp^n}\right]_{p=0}, \quad n = 0,\ 1,\ 2,\ \ldots \tag{10}$$

are the constant coefficients.

Thus, substituting coefficients A_n, B_n and C_n found from formulae (10) to expansions (9), and then summing up the results, according to (8), we will obtain the estimate of accuracy of arc self-adjustment, $\varepsilon_\infty(t)$.

If, for example, in expressions (9) we don't go beyond the first two terms of a series, which is quite acceptable in our case, then the approximate estimate of accuracy $\varepsilon^*_\infty(t)$ will take a relatively simple form, such as

$$\varepsilon^*_\infty(t) = T_sDv_e + DH - \frac{1}{E}Du_s. \tag{11}$$

Numerical values of parameters T_s and E, as well as the rate of changes in input actions $v_e(t)$, $H(t)$ and $u_s(t)$ being known, we can easily calculate deviation $\varepsilon^*_\infty(t)$ from formula (11), i.e. obtain the estimate of accuracy of arc self-adjustment in each particular case without any additional theoretical or experimental investigations.

It can be directly seen from expression (11) that if $v_e = \text{const}$, $H = \text{const}$ and $u_s = \text{const}$, then deviation $\varepsilon_\infty(t)$ in the steady-state mode equals zero. Obviously, at $v_e(t) \neq \text{const}$, the lower the value of time constant T_s, which depends, according to (2), (3), on the slope of volt-ampere characteristics of the arc, $S_a \equiv \partial u_a/\partial i$, and welding current source, $S_s \equiv \partial u_s/\partial i$, the slope of electrode melting characteristic $M \equiv \partial v_m/\partial i$ and intensity of the electric field in the arc column, $E \equiv \partial u_a/\partial l$, the smaller is value of deviation $\varepsilon_\infty(t)$. It can be easily seen from (11), (2) and (3) that the lower the value of $R_* = R + S_a - S_s$ and higher the value of EM, the lower is the value of deviation $\varepsilon_\infty(t)$ in the steady-state mode, i.e. the higher is the accuracy of arc self-adjustment.

As for time τ of the transient process, which is another main characteristic of quality of self-adjustment of the arc, since $T_s >> T_e$ in the welding circuit, this time can be estimated from the following formula:

$$\tau^* = T_s \ln (k), \tag{12}$$

where k is the number determining the degree of decrease of initial deviation ε_0 during desired time τ, i.e. $k = \varepsilon_0/\varepsilon(t)$.

It is follows from formulae (12), (2), (3), in particular, that time τ of the transient process reduces with decrease of R_* and increase of EM.

Thus, formulae (11) and (12) are very convenient for numerical estimation of the quality of the arc self-adjustment process, which to a certain extent determines the quality of the arc welding process.

Results of computer modeling of the processes described by differential equation (1) are shown in Figures 1 and 2. The following values of parameters of the welding circuit and mode of arc welding are taken: $L = 4\cdot10^{-4}$ H; $R = 0.015$ Ohm; $E = 2$ V/mm; $M = 0.31$ mm/(A·s), and $S_a = 0.005$ V/A.

Transient and steady-state processes $\varepsilon(t)$ obtained in changing of electrode feed speed $v_e(t)$ and at constant $H = 17$ mm and $u_s = 30$ V, are shown in Figure 1. For simplicity of verification of formula (11), the law of change in $v_e(t)$ was set by the dependence

$$v_e(t) = \begin{cases} 45, & t < 0.5 \\ 45 + 20(t - 0.5), & t \geq 0.5 \end{cases} \text{[mm/s]}.$$

Comparison of curves *1* and *2* in Figure 1 shows that the arc self-adjustment accuracy characterized by

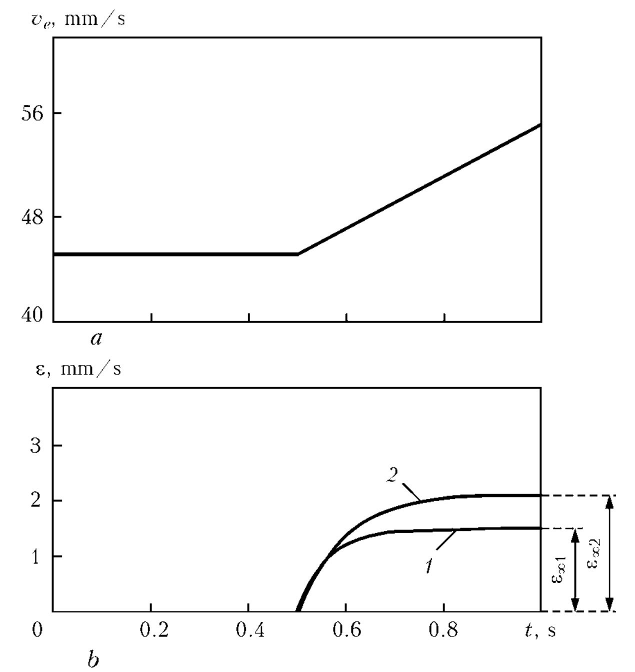

Figure 1. Linear change in electrode feed speed v_e (*a*), and response of deviation $\varepsilon(t)$ to this change (*b*): *1* — $S_s = -0.025$; *2* — -0.045 V/A

deviation $\varepsilon(t)$ increases with decrease in slope S_s of volt-ampere characteristic of the welding current source.

Transient process $\varepsilon(t)$ induced by a stepwise change in distance $H(t)$ between the tip of the current-conducting nozzle and free surface of the weld pool is shown in Figure 2:

$$H(t) = \begin{cases} 17, & t < 0.5 \\ 20, & t \geq 0.5 \end{cases} \text{[mm]}.$$

Voltage u_s was set to be equal to 30 V, and speed v_e — to 45 mm/s.

It can be seen from Figure 2 that the time of the transient process reduces with decrease in slope S_s of volt-ampere characteristic of the welding current source.

To illustrate the efficiency of application of formulae (11) and (12) for numerical estimation of the arc self-adjustment quality, calculate steady-state deviation $\varepsilon_\infty^*(t)$ and time τ of the transient process from these formulae for the above cases.

In case of a linear change in electrode feed speed $v_e(t)$ (see Figure 1)

$$\varepsilon_{\infty 1}^*(t) = T_s D v_e = \frac{0.015 + 0.005 + 0.025}{2 \cdot 0.31} \times$$
$$\times\ 20 = 1.45 \text{ mm/s (curve } \mathit{1});$$

$$\varepsilon_{\infty 2}^*(t) = \frac{0.015 + 0.005 + 0.045}{2 \cdot 0.31} \times$$
$$\times\ 20 = 2.1 \text{ mm/s (curve } \mathit{2}).$$

In case of a stepwise change in distance $H(t)$ between the tip of the current-conducting nozzle and free surface of the weld pool (see Figure 2)

$$\tau_1^* = T_s \ln(k) = \frac{0.015 + 0.005 + 0.015}{2 \cdot 0.31} \times$$
$$\times\ 3 = 0.17 \text{ s (curve } \mathit{1});$$

$$\tau_2^* = \frac{0.015 + 0.005 + 0.045}{2 \cdot 0.31} \times$$
$$\times\ 3 = 0.31 \text{ s (curve } \mathit{2}).$$

Comparing $\varepsilon_\infty^*(t)$ and τ^* calculated from formulae (11) and (12) with corresponding values of ε_∞ and τ obtained by modeling (Figures 1, 2): $\varepsilon_{\infty 1}(t) = 1.45$ mm/s, $\varepsilon_{\infty 2}(t) = 2.09$ mm/s, $\tau_1 = 0.16$ s, $\tau_2 = 32$ s, it can be seen that they almost coincide.

Therefore, the computer modeling and the above calculations show that estimations (11) and (12) proposed in this study give a clear idea of the accuracy and time of the transient arc self-adjustment processes. Parameters of the welding circuit being known, it is easy to calculate the values of ε_∞^* and τ^* from formulae

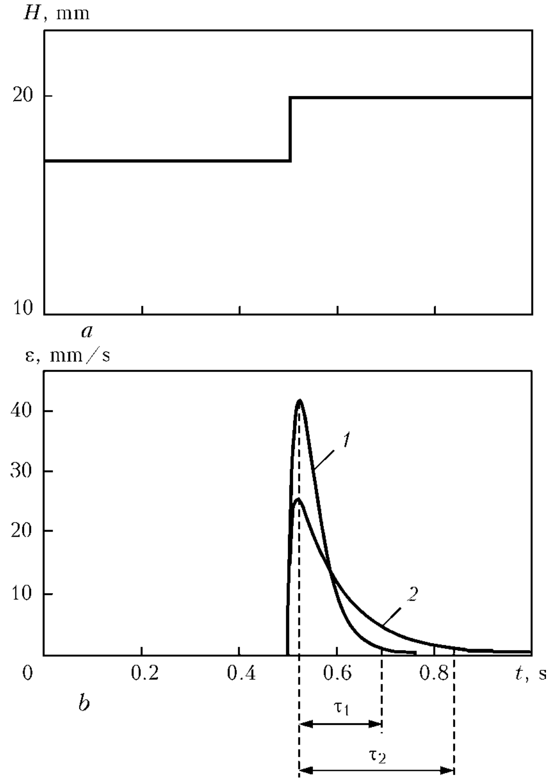

Figure 2. Stepwise change in distance H between the nozzle and weld pool (*a*), and response of deviation $\varepsilon(t)$ to this change (*b*): *1* — $S_s = -0.015$; *2* — -0.045 V/A

(11) and (12). Moreover, having the above formulae, the desirable indicators of the arc self-adjustment quality can be provided by selecting certain relationships between parameters of the welding circuit. Such a necessity, in particular, arises when using the pulsed arc welding methods [10].

We used estimations (11) and (12) in [11] for the development of the adaptive arc sensor to provide corrective control of robotized arc welding.

1. Paton, B.E. (2008) *Selected transactions*. Kiev: PWI.
2. Dyurgerov, N.G. (2001) Integral criterion of the welding arc self-adjustment quality. *Svarochn. Proizvodstvo*, **8**, 8–10.
3. Popov, E.P. (1987) *Theory of linear systems of automatic regulation and control*. Moscow: Nauka.
4. King, L.G. (1954) Decrease of steady dynamic error in closed tracking systems. *Prikl. Mekhanika i Mashinostroenie*, **2**, 3–14.
5. Lukas, V.A. (1990) *Theory of automatic control*. Moscow: Nedra.
6. Tumanov, M.P. (2005) *Theory of control. Theory of automatic control linear systems*. Moscow: MGIEM.
7. (1951) *Theory of tracking systems*. Ed. by H. James et al. Moscow: Inostr. Literatura.
8. Tsybulkin, G.A. (1994) Analysis of steady-state modes of some classes of nonlinear dynamic systems based on recurrent estimation procedures. *Kibernetika i Vychisl. Tekhnika*, Issue 101, 74–80.
9. Tsybulkin, G.A. (2008) Stabilization of electrode melting rate in robotic arc welding. *The Paton Welding J.*, **12**, 9–11.
10. Kiji, N., Kobayashi, K., Ishii, J. et al. (2003) Development of high-efficiency arc welding methods. *Ibid.*, **10/11**, 56–60.
11. Tsybulkin, G.A. (2001) Robust digital sensor for arc welding. *Ibid.*, **11**, 44–46.