INDICATORS OF STABILITY OF THE GMAW PROCESS

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Formulation of the term of stability of the GMAW process is offered. Objective indicators of stability are considered and analysed. A set of indicators of the process stability is suggested for each welding method and character of metal transfer.

Keywords: *arc welding, metal electrode, welding process quality, welding process stability, indicators of stability*

One of the main indicators of quality of the gas metal-arc welding (GMAW) process is its stability, which is closely related to such quality indicators as spattering and quality of weld formation. No generally accepted formulation of the notion of stability of the welding process exists now. Every researcher understands stability of the process in his own way and, therefore, uses differing indicators of stability.

The purpose of this study is to formulate the notion of stability of the GMAW process and choose the indicators of stability depending on the welding method and type of transfer of the electrode metal into the weld pool.

Several different definitions of the «welding process stability» term are available. GOST 25616–83 (ST SEV 3235–81) mentions the «welding process stability» term only for manual stick electrode welding, but gives no formulation for it [1]. Later on, developers of these standards formulated the «welding process stability» term for manual and mechanised welding as follows [2, 3]: «Term «the stable welding process» implies a process which provides quality formation of a welded joint with the sufficiently smooth surface and main parameters that are practically constant along its entire length — penetration depth, and bead width and height». The authors of study [4] offered a close definition: «It is generally agreed that the stable welding process is a process which provides constancy of geometric sizes of the weld or their deviation within the permissible limits». In fact, this is a formulation of a consequence of stability of the welding process, rather than the stability of this process. According to this formulation, it is very difficult to automatically measure stability indicators directly during the welding process.

In the broad sense the Latin word «stabilis» means constant, steady. For example, studies [5–8] make no difference between notions «stable» and «steady», while study [9] gives the following definition: «The spatial steadiness of the arc is called stability of the arc». However, terms «stable» and «steady», as a rule, are not considered synonyms in modern technical literature.

It is generally accepted that the steady process is a process that returns to the equilibrium state after any, rather small initial deviation caused by the effect of external disturbances. In welding, this notion is used to analyse of the so-called arc process self-regulation phenomenon.

Stability of a technological process usually means a property of the latter that provides constancy of the probability distribution for its parameters during a certain period of time without any interference from outside [10]. In other words, the process the deviation of parameters of which from the mean values does not exceed the specified level is called stable. Accordingly, the measure of stability of the process is deviation of its parameters from the mean values. Normally, the following variance is taken as a measure of deviation of a discrete signal from mean value $\bar{x}$:

$$\sigma^2(x) \approx \frac{1}{n-1} \sum_{i}^{n} (x_i - \bar{x})^2,$$

where n is the quantity of changes, or $\sigma(x) = \sqrt{\sigma^2(x)}$ is the standard deviation, or variation coefficient $K_V(x) = \sigma(x)/\bar{x}$.

Most often the welding process stability is considered to be stability of the arc and stability (regularity) of transfer of the electrode metal into the weld pool.

The set of the indicators used to characterise the welding process stability depends on the welding method and method of transfer of the electrode metal into the weld pool.

Manual covered-electrode welding. In the majority of cases only one indicator is used for this welding method — stable or unstable arc. Expert estimation of stability of the arc according to the three- [6] or four-point system is sometimes used, as recommended in GOST 25616–83 (ST SEV 3235–81) [1]. Independently of the kind of the welding current, the welding process stability is assessed by a test welder according to the frequency of extinctions of the arc, uniformity of its burning, vibration and sounding of the arc. The standard contains no clear definitions what exactly the uniformity of burning and vibration of the arc mean. Needless to say that inherently the expert estimates are subjective and require that experts be highly qualified.

In principle, visual and acoustic parameters of stability of the welding process mentioned in standard [1] can be fixed by using instruments and then mathematically processed to obtain quantitative estimates. Thus, sounding of the arc is determined with a microphone, and light emission — with a corresponding photodetector. Acoustic emission (sounding of the welding arc, the intensity and character of which is used to evaluate stability of the welding process) results from oscillations of the surface of the arc column. The intensity of sounding of the arc is proportional to the rate of oscillations of its power, i.e. the rate of variations in the arc current [11]. Variations in the light emission are determined by oscillations of the arc power as well. Therefore, the light and acoustic emissions of the arc as parameters of instability of the welding process are secondary with respect to the electric parameters, i.e. welding current I_w and arc voltage V_a. Naturally, for this reason it is better to use I_w and U_a for objective estimation of the arc stability, as they are easier to measure compared to the light and acoustic emissions. Instrumental determination of the arc extinctions from the voltage or current is not difficult either.

Manual AC covered-electrode welding. In AC welding, as value of the current falls to zero in each half-period of the mains voltage, this causes extinction of the arc, which again ignites after some time. Such natural extinctions of the arc do not always end with its repeated ignition in the next half-period of the supply voltage. As a result, AC welding is the most unstable process out of all welding processes, while frequency of the arc extinctions is, undoubtedly, the main objective indicator of its burning.

E.M. Kuzmak [12] was the first to offer using the frequency of extinctions of the arc to characterise stability of its burning. Later on, study [13] used the number of the arc extinctions per electrode length, N_{ext}, and study [14] used that per electrode unit length. No doubt, the relative number of the arc extinctions is a direct numeric parameter of stability of the arc burning at the alternating current.

In addition to the frequency of the arc extinctions, there are many indirect parameters suggested to characterise not the arc stability proper, but the probability of the repeated arc ignition. Mainly, these are the parameters that characterise residual plasma after extinction of the arc and electric characteristics of the welding circuit responsible for the repeated arc ignition.

G.I. Leskov suggested that stability of the arc for electrodes with different coverings should be estimated from the initial rate of growth of the current at its repeated ignition, di_2/dt [15]. The higher the value of this indicator, the more stable is considered to be the arc burning [7]. This indicator is determined from phase characteristic $di/dt = f(i)$.

As the rate of variations in the welding current when it passes through zero is determined, to a significant degree, by its effective value, to exclude the effect of the latter V.Yu. Arlauskas and I.R. Narushkevichyus [8] offered the following dimensionless indicator of stability of the arc ignition:

$$K_i = \frac{di_2/dt}{di_1/dt}\, 100\ \%,$$

where di_1/dt is the maximal rate of decay of the welding current before the arc extinction. According to this indicator, an ideal stability of the arc takes place at $K_i = 100$ %.

Not all researchers consider the use of these indicators efficient for evaluation of stabilising properties of welding consumables. For example, in the opinion of V.A. Troitsky [16], growth of the pre-arc and arc currents greatly depends on the linearity of a source, and the rate at which the current passes through zero is determined only by the electric characteristic of the welding source.

Another indicator of the arc stability in welding without short circuits is given in study [17]: $B_i = I_i/(U_i t_i)$, where U_i and I_i are the voltage at electrodes and current in the inter-electrode gap at the moment of recovery (ignition) of the arc discharge, and t_i is the time of interruption of the arc burning (ignition). The higher the value of this indicator, the more stable is considered to be the arc.

For manual arc welding without short circuits, I.I. Zaruba and V.V. Dymenko [18] offered the following indicator of the arc stability: $K_{st} = I_{cr}/\tau$, where I_{cr} is the critical arc current at the moment of extinction and passage of the electrode metal droplet through the arc, below which the arc may go out, and τ is the critical time during which the arc plasma will most likely be destroyed as a result of the metal transfer. Detachment of a droplet at the end of half-period of the welding current may lead to the point that the latter will disappear earlier than its value will naturally pass through zero, this being accompanied by increase in no-current time range t_i. In contrast to the previous stability indicators, K_{st} characterises the probability of the repeated ignition of the arc after its extinction and transfer of the electrode metal droplet.

Except for the frequency of the arc extinctions, strictly speaking, none of the offered indicators is an indicator of the arc stability or stability of the welding process as a whole. For the alternating current, its mean value is equal to zero. Therefore, standard deviation of the current is not an indicator of its stability, but a measure of its value, and is called the effective value of current I. In this case, variance $\sigma^2(I)$, standard deviation $\sigma(I)$ or coefficient of variation of the effective value of the welding current, K_V^I, can be used as an objective indicator of the welding process stability, according to the above definition of stability. Similarly, variance $\sigma^2(U)$, standard deviation $\sigma(U)$ or coefficient of variation of the effective value of voltage at electrodes, K_V^U, can be used as a stability indicator for the arc voltage drop. These parameters are indicators of the process stability only in welding without regular short circuits.

In manual arc welding, metal transfer takes place mostly with regular short circuits [15, 19]. Naturally, the presence of short circuits affects variations of the effective values of the welding current and arc voltage. Moreover, these variations may be higher or lower than the variations caused by the effect of other disturbances. Therefore, variations in the welding current and arc voltage are insufficiently sensitive to instability of the short circuits. Stability of the short circuits can be more efficiently evaluated from the standard deviation of their frequency $\sigma(f_{\mathrm{s.c}})$ and duration $\sigma(\tau_{\mathrm{s.c}})$. If welding parameters provide for the absence of regular short circuits, the instability of the process because of short circuits should be estimated from the value of $f_{\mathrm{s.c}}$: the higher this value, the more stable is the welding process.

Manual DC covered-electrode welding. For the first time the quantitative estimation of the arc stability was suggested by K.K. Khrenov [6], who assessed stability of the arc from its length at extinction: the longer the arc at extinction for a fixed electrode, the smaller is the number of the arc extinctions during welding and, therefore, the more stable is the arc. This method has a drawback consisting in the errors caused by the effect of the droplets that had no time to detach from the electrode tip before the arc extinction. The method gives a scatter of 15–30 % [7]. Strictly speaking, the length of the arc at extinction is a measure of its elasticity, which is singled out as a separate indicator of quality of the arc [1], and is only indirectly related to the frequency of the latter. Different authors use different statistical parameters of the welding current and arc voltage as a measure of uniformity of arcing to estimate the arc stability.

For instance, V.M. Yazovskikh and co-authors suggested using variance $\sigma^2(I_{\mathrm{w}})$ [20], standard deviation $\sigma(I_{\mathrm{w}})$ or welding current variation coefficient $K_V^{I_{\mathrm{w}}}$ [21, 22] as stability indicators. The authors are of the opinion that the lower the value of these parameters, the more stable is the arc.

Study [5] checked the possibility of estimation of the arc stability from $\sigma^2(U_{\mathrm{a}})$. It is the opinion of the authors that this indicator does not correlate with the arc stability in DC covered-electrode welding.

Mechanised DC gas-shielded arc welding. Most publications relate to stability of welding with short circuits, as the welding process with a spray metal transfer is stable in its nature, and that with a drop metal transfer is unstable. In this connection, the trend is not to apply the last welding method.

In CO_2 or gas mixture shielded short-arc welding the molten metal is transferred from the electrode into the weld pool in short circuiting of the arc gap. As a result, the instantaneous values of the welding current and arc voltage periodically vary over wide ranges. Numerous investigations were carried out to study the welding current and arc voltage to identify the indicators reflecting the welding process stability. For this, the primary consideration was given to statistical parameters of the welding current and arc voltage. The list of these parameters that is far from being complete is given in Table 1.

It is thought that the lower the value of any of these parameters, the more stable is the welding process. However, this is not always true for some of the parameters.

In metal-electrode short-arc welding with periodic short circuits of the arc gap, pulse welding or modulated current welding the arc voltage and welding current are inherently of a pulse character, i.e. they periodically change their values. In definition, any periodically changing (modulated) signal has values of σ^2, σ and K_V other than zero. To illustrate, Figure 1, *b* and *c* shows results of modelling of the welding current and arc voltage in metal-electrode welding with periodic short circuits (Figure 1, *a*). Modelling was performed for open-circuit voltage $E1 = 20$ V, voltage $E2 = 12$ V that depends on the near-electrode voltage drop and arc length, internal active resistance $R1 = 0.05$ Ohm of the power supply and welding circuit, electrode extension resistance $R2 = 0.05$ Ohm, arc column resistance $R_{\mathrm{a}} = 0.025$ Ohm, and $\tau = 20$ ms.

Figure 2 shows dependence of $K_V^{I_{\mathrm{w}}}$ and $K_V^{U_{\mathrm{a}}}$ on duty factor $D = \tau_{\mathrm{s.c}}/\tau$ and inductance L of choke of the device (see Figure 1, *a*). The curves are given for an ideally stable process of transfer of the molten metal into the weld pool at a constant frequency of short circuits. It can be seen from Figure 2 that even with the ideally stable process, $K_V^{I_{\mathrm{w}}}$ and $K_V^{U_{\mathrm{a}}}$ have rather high values, which vary over wide ranges depending on the parameters of the welding circuit and welding conditions. Naturally, instability of the welding process, i.e. random variations in the short circuit frequency, short circuit time, arc length and other parameters, leads to increase in the variation coefficient, compared to the ideally stable welding process. But their effect on $K_V^{I_{\mathrm{w}}}$ and especially on $K_V^{U_{\mathrm{a}}}$ is insignificant. As an example, below we give values of $\sigma(U)$ for rectangular pulses of unit amplitude of $U_{\max}$ and duty factor $D = t_{\mathrm{p}}/T = 0.7$ at random variations in pulse amplitude T and pulse duration τ_{p}. The normal distribution law with standard deviations of $\sigma(U_{\max})$ and $\sigma(t_{\mathrm{p}})$ is accepted for the pulse amplitude and duration.

As seen from the below data, instability of the arcing time has almost no effect on $\sigma(U)$:

Table 1. Published data on indicators of stability of arc welding processes

Parameter of welding process stability	Welding method with short circuits	Reference
$\sigma^2(U_a)$	In CO_2	[23]
$\sigma(U_a)$	Same	[24]
$K_V^{U_a}$	»	[3, 25]
$C_V^{U_a}$	»	[25]
$\sigma(I_w)$	»	[24]
$K_V^{I_w}$	»	[3, 25]
$C_V^{I_w}$	»	[25]
$\sigma(I_{max})$	In CO_2, in gas mixtures	[26, 27]
$\sigma(I_{min})$	In gas mixtures	[28]
$K_V^{I_{max}}$	In CO_2	[2, 29]
$\sigma^2(\tau_{s.c})$	Same	[23]
$\sigma(\tau_{s.c})$	Same In CO_2, in gas mixtures	[24] [27]
$K_V^{\tau_{s.c}}$	In CO_2 In gas mixtures	[3, 30] [31]
$\sigma^2(\tau_a)$	In CO_2	[23]
$\sigma(\tau_a)$	Same In gas mixtures	[24] [27]
$K_V^{\tau_a}$	In CO_2 In gas mixtures	[30] [31]
$\sigma^2(f_{s.c})$	In CO_2	[32]
$N_{s.c}^r$	In gas mixtures	[31]
$\sigma(\tau)$	In CO_2, in gas mixtures In gas mixtures without short circuits	[26, 27, 33] [34]
$\sigma(U_a^a)$	With short arc in CO_2	[23]
$\sigma(U_a^{s.c})$	Same	[23]
$\overline{\tau}_{s.c}$	In CO_2	[3]
$K_V^{\tau_{ext}}$	Same	[30]
$(I_w - U_a)$ diagram	In gas mixtures without short circuits	[31]
9th and 10th quantiles of density of distribution of U_a	Same	[24]
9th and 10th quantiles of density of distribution of I_w	»	[24]

Note. $C_V^{U_a} = K_V^{U_a}/f_{s.c}$ — coefficient of variation of welding voltage related to short circuit frequency; I_{max} — amplitude of short-circuit current; $C_V^{I_w} = K_V^{I_w}/f_{s.c}$ — coefficient of variation of welding current related to short circuit frequency; $\tau_{s.c}$ — duration of effective short circuit; $\overline{\tau}_{s.c}$ — average duration of all short circuits; τ_a — duration of arcing between short circuits; τ — standard deviation of short circuit duration; $\tau = \tau_{s.c} + \tau_a = 1/f_{s.c}$; $N_{s.c}^r = n_{s.c}^r/n_{s.c}^0$ — relative number of random short-time (with duration of less than 1.5 ms) short circuits, i.e. short circuits at which no metal transfers to the weld pool; $n_{s.c}^r$ — number of random short circuits; $n_{s.c}^0$ — total number of short circuits; U_a^a — voltage in the arcing phase; $U_a^{s.c}$ — voltage during a short circuit; $K_V^{\tau_{ext}} = \sigma(\tau_{ext})/\tau_{ext}$ — coefficient of variation of arc extinction duration τ_{ext}.

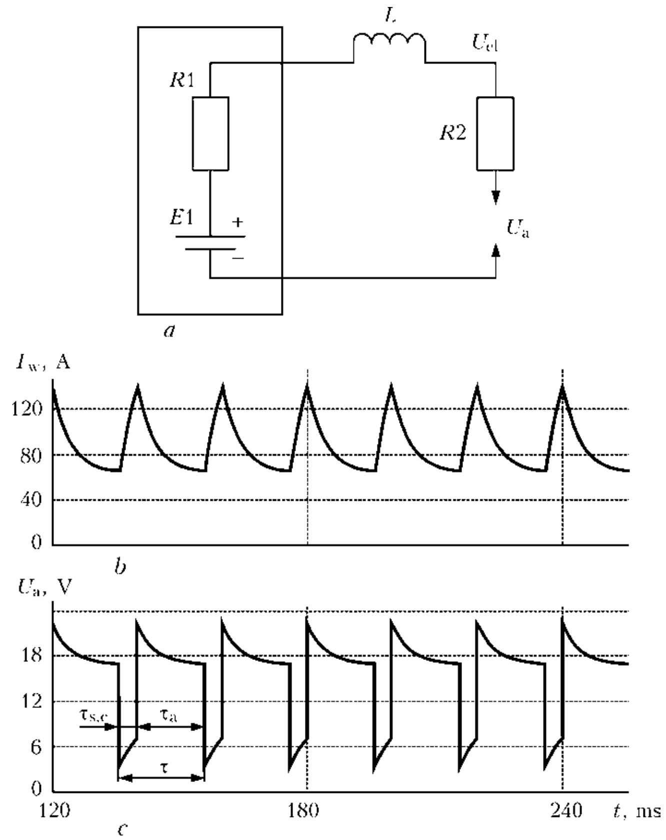

Figure 1. Equivalent circuit of power supply with a welding circuit (*a*), and oscillograms of welding current I_w (*b*) and arc voltage U_a (*c*) ($U_a = E_a + R_aI_w$)

$\sigma(t_p)$	0	0.05	0.10	0.15	0.20
$\sigma(U)$	0.25099	0.25106	0.25111	0.25118	0.25124

In oscillations of the pulse amplitude, variance $\sigma^2(U_{max})$ is summed up with variance $\sigma_0^2(U)$ caused only by short circuits ($\sigma^2(U_{max}) = 0$):

$\sigma(t_{max})$	0	0.05	0.10	0.15	0.20
$\sigma(U)$	0.25099	0.25477	0.26527	0.28172	0.30316

Therefore, in welding with periodic short circuits, pulse welding and modulated-current welding the values of σ^2, σ and K_V of the welding current (voltage) characterise mostly the shape and parameters of modulation of the welding current (voltage) and, to a lesser degree, stability of the welding process.

The above drawbacks of $\sigma(U_a)$ will not take place, providing that the standard deviations of voltage only during the short circuits, $\sigma(U_a^{s.c})$, and arcing, $\sigma(U_a^a)$, are used separately [24].

In welding without regular short circuits, σ^2, σ and K_V are, by definition, the indicators of the welding process stability reflecting in addition such instabilities as arc extinctions and short circuits. However, if these disturbances are relatively infrequent, then, as follows from Figure 2, they will have a low effect on σ^2, σ and K_V. In this case, it is more expedient to directly measure short circuit frequency $f_{s.c}$ and arc extinctions f_{ext} as the stability indicators.

It should be borne in mind that the accuracy of estimation of the process stability in welding without short circuits from the values of σ^2, σ and K_V decreases because of interferences caused by pulsations of voltage of the welding power supply. In six-phase bridge rectifiers that are characteristic of the thyristorised welding power supplies, the ratio of the effective value of fundamental harmonic (300 Hz) to the mean value of rectified open-circuit voltage may vary from 0.05 to 0.37, depending on the switching angle of the thyristors [35]. In this case, an efficient means for improving the accuracy of estimation of parameters of the welding process stability is filtering of these interferences, as the frequency of variations in the welding current and voltage caused by instability of the welding process proper is rarely in excess of 200 Hz.

Study [31] suggests that the I_w–U_a diagram should be analysed to identify such instabilities of the welding process in gas mixtures as random short-time short circuits, abnormal increase in voltage during repeated ignition of the arc after a short circuit, and arcing between the short circuits.

Standing apart is another, rather exotic stability indicator suggested in study [24]. It is a difference between the 9th and 10th quantiles of density of distribution of the arc voltage and welding current. The lower the values of these quantiles, the higher is the stability of the gas mixture-shielded welding process with short circuits.

As follows from Table 1, the most popular indicators for estimation of stability of the welding process with short circuits are stability parameters $f_{s.c}$ and $\tau_{s.c}$. It can be shown that these parameters reflect stability of transfer of the electrode metal into the weld pool. In fact, the stable GMAW process is characterised by an unfailing observance of the equality of a mean volume electrode melting rate and volume electrode feed rate:

$$\overline{v}_f S_{el} = f_{s.c} Q_d,$$

where $\overline{v}_f$ is the linear rate of feed of the electrode wire; S_{el} is the electrode cross section area, and Q_d is the volume of a droplet. If distributions of variables $\overline{f}_f$, S_{el} and Q_d are normal, and their standard deviations are independent, based on the above formula it can be written down for the short circuit frequency standard deviation that

$$\sigma(f_{s.c}) = \sqrt{\left(\frac{S_{el}}{Q_d}\right)^2 \sigma^2(v_f) + \left(\frac{v_f}{Q_d}\right)^2 \sigma^2(S_{el}) + \left(\frac{v_f S_{el}}{Q_d^2}\right)^2 \sigma^2(Q_d)}.$$

It can be seen from this dependence that $\sigma(f_{s.c})$ directly characterises instability of the electrode wire feed rate, wire cross section area and droplet volume. As instability of the first two parameters is not high, $\sigma(f_{s.c})$ is mainly a measure of instability of the droplet volume.

As $f_{s.c} = 1/(\tau_{s.c} + \tau_a)$, similar dependencies can also be derived for $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$:

$$\sigma^2(\tau_{s.c}) + \sigma^2(\tau_a) = \left(\frac{1}{v_f S_{el}}\right)^2 \sigma^2(Q_d) + \left(\frac{Q_d}{v_f^2 S_{el}}\right)^2 \sigma^2(v_f) + \left(\frac{Q_d}{v_f S_{el}^2}\right)^2 \sigma^2(S_{el}).$$

As a characteristic of instability of $\overline{v}_f$, S_{el} and Q_d, this formula has no advantages over the previous one. Hence, it is enough to estimate only $\sigma(f_{s.c})$. However, it is absolutely obvious that, in addition to instability of the droplet volume, $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$provide information on fluctuations of other parameters of the welding process as well. For example, $\sigma(\tau_{s.c})$ depends on the instability of shape of the droplet, variations in its position on the electrode tip, instability of shape of the short circuit current, oscillations of the weld pool surface, etc. In turn, the $\sigma(\tau_a)$ values depend on variations in the electrode extension, oscillations of the welding current and arc voltage drop, volume of the molten metal remaining on the electrode tip in repeated ignition of the arc after a short circuit, etc. Therefore, collectively $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$ provide a more comprehensive characterisation of stability of the welding process with short circuits than only $\sigma(f_{s.c})$.

Table 2 gives parameters of stability of the GMAW process recommended on the basis of the above-said. The lower the value of the given parameters, the higher is the stability of the welding process. All of the above indicators of the welding process stability can be determined by processing only the arc voltage and welding current values.

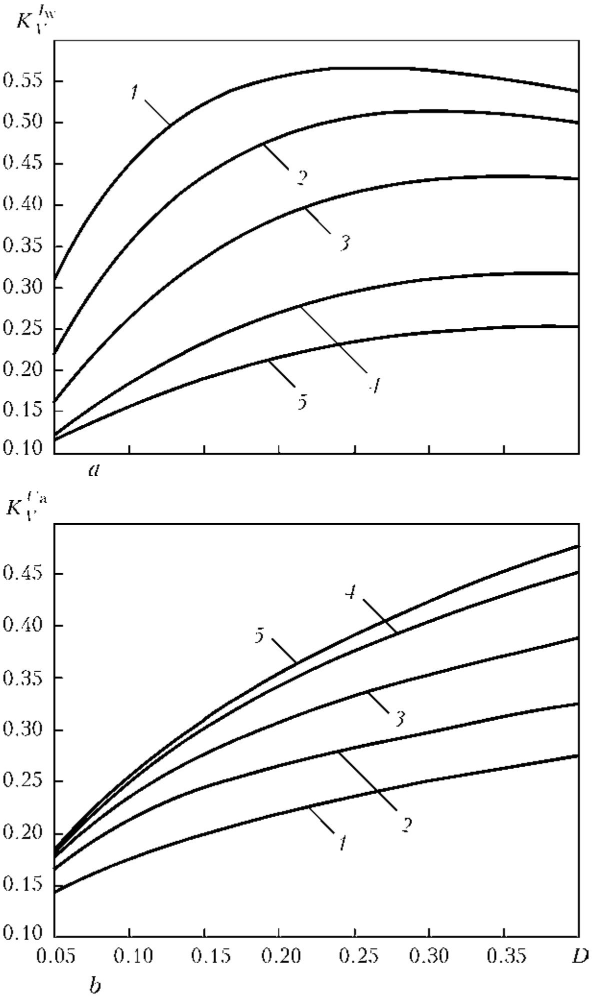

Figure 2. Dependence of coefficients of variations of welding current $K_V^{I_w}$ (*a*) and arc voltage $K_V^{U_a}$ (*b*) on duty factor D at different values of the device choke inductance (see Figure 1, *a*): *1* — L = = 0.050; *2* — 0.125; *3* — 0.250; *4* — 0.500; *5* — 0.750 mH

Pulse welding and modulated current welding. The following parameters in different combinations, depending on the mode of operation of the welding power supply (stabilisation of current or voltage), can serve as indicators of the process stability for the above welding methods: $K_V^{I_p}$, $K_V^{I_b}$, $K_V^{U_p}$ and $K_V^{U_b}$, where I_p is the pulse current; I_b is the base current; U_p is the pulse voltage, and U_b is the base voltage.

As stability of the welding process is characterised by several indicators, this makes it necessary to form one integrated indicator (objective function) from them by using the significance coefficient for each indicator.

The following functional dependence is used for this: $\gamma = f(n, b_i, k_i)$, $i = 1, 2, 3, \ldots, n$, where n is the quantity of the accountable unit indicators; b_i is the coefficient of significance of the i-th indicator, and k_i is the i-th indicator.

Table 2. Recommended parameters of stability of the GMAW process

Welding process stability parameter	Manual welding			Automatic and mechanised gas-shielded welding	
	Alternating current	Direct current			
		With short circuits	Without short circuits	With short circuits	Without short circuits
N_{ext}	+	–	–	–	–
$f_{\mathrm{s.c}}$	–	–	+	–	+
$f^{\mathrm{f}}_{\mathrm{s.c}}$	–	+	–	+	–
$\sigma^2(I) \vee \sigma(I) \vee K_V^I$	+	–	–	–	–
$\sigma^2(U) \vee \sigma(U) \vee K_V^{U_{\mathrm{a}}}$	+	–	–	–	–
$\sigma^2(I_{\mathrm{w}}) \vee \sigma(I_{\mathrm{w}}) \vee K_V^{I_{\mathrm{w}}}$	–	–	+	–	+
$\sigma^2(U_{\mathrm{a}}) \vee \sigma(U_{\mathrm{a}}) \vee K_V^{U_{\mathrm{a}}}$	–	–	+	–	+
$\sigma^2(I_{\mathrm{w}}^{\mathrm{s.c}}) \vee \sigma(I_{\mathrm{w}}^{\mathrm{s.c}}) \vee K_V^{I_{\mathrm{w}}^{\mathrm{s.c}}}$	–	+	–	+	–
$\sigma^2(I_{\mathrm{w}}^{\mathrm{a}}) \vee \sigma(I_{\mathrm{w}}^{\mathrm{a}}) \vee K_V^{I_{\mathrm{w}}^{\mathrm{a}}}$	–	+	–	+	–
$\sigma^2(U_{\mathrm{a}}^{\mathrm{s.c}}) \vee \sigma(U_{\mathrm{a}}^{\mathrm{s.c}}) \vee K_V^{U_{\mathrm{a}}^{\mathrm{s.c}}}$	–	+	–	+	–
$\sigma^2(U_{\mathrm{a}}^{\mathrm{a}}) \vee \sigma(U_{\mathrm{a}}^{\mathrm{a}}) \vee K_V^{U_{\mathrm{a}}^{\mathrm{a}}}$	–	+	–	+	–
$\sigma^2(f_{\mathrm{s.c}}) \vee \sigma(f_{\mathrm{s.c}}) \vee K_V^{f_{\mathrm{s.c}}}$	–	+	–	+	–
$\sigma^2(\tau_{\mathrm{s.c}}) \vee \sigma(\tau_{\mathrm{s.c}}) \vee K_V^{\tau_{\mathrm{s.c}}}$	–	+	–	+	–
$\sigma^2(\tau_{\mathrm{a}}) \vee \sigma(\tau_{\mathrm{a}}) \vee K_V^{\tau_{\mathrm{a}}}$	–	+	–	+	–

Note. 1. $f^{\mathrm{f}}_{\mathrm{s.c}}$ — frequency of false short circuits. 2. Sign + shows applicability, and sign — shows inapplicability of parameter depending on the welding method and type of transfer of the electrode metal into the weld pool.

Function of the type of $\gamma = \sum_i^n b_i k_i$ is normally used, and function $\gamma = \prod_i^n k_i^{b_i}$ is used very rarely. An important element of formation of the integrated indicator is setting of the values of the significance coefficients. Dozens of methods for determining them are available [36, 37], the most common one among them being an expert estimation of the significance coefficients.

Only one integrated indicator has been suggested so far to characterise stability of the welding process (CO_2 welding with short circuits) [30]:

$$\gamma = k_0 K_V^{\tau_{\mathrm{exp}}} + k_1 K_V^{\tau_{\mathrm{s.c}}} + k_2 K_V^{\tau_{\mathrm{a}}},$$

where k_0 is the relative total time of the arc extinctions; and k_1 and k_2 are the relative total times of the short circuits and arcing, respectively.

The minimal value of coefficient γ corresponds to the maximum stable welding process. It should be noted that this integrated stability indicator allows for the arc extinctions that take place mostly in the beginning of welding at excitation of the arc. Standard [1] sets off reliability of establishing of the welding process (initial arc ignition) as a separate indicator of welding properties of the power supplies, which is not related to indicators of the welding process stability. In addition, the choice of k_0, k_1 and k_2 as the significance coefficients should not be considered the only possible one.

Study [38] offers a simple integrated parameter of the welding process stability:

$$PR = \frac{I_{bk} U_{bk}}{I_{\mathrm{mean}} U_{\mathrm{mean}}},$$

where I_{mean} and U_{mean} are the mean values of the welding current and arc voltage; U_{bk} is the arithmetic mean of digitised value of the arc voltage lower than U_{mean} within the measurement range, and I_{bk} is the arithmetic mean of digitised value of the welding current lower than I_{mean}.

To provide the stable process, it is required that $0.2 < PR < 0.4$ (process with short circuits), $0.8 < PR < 0.9$ (drop metal transfer) and $0.95 < PR < 0.98$ (spray metal transfer). In the intermediate zones the welding process is unstable and characterised by increased spattering.

Also, the above study offers the stability criteria in the form of a set of rules based on the following three dimensionless parameters:

$$TI = 1 - \frac{I_{\min}}{I_{\mathrm{mean}}}, \quad TSI = \frac{I_{\max}}{I_{\mathrm{mean}}}, \quad DCI = 1 - \frac{U_{bk}}{U_{\mathrm{mean}}},$$

where $I_{\max}$ and $I_{\min}$ are the maximal and minimal values of the welding current, respectively. These rules are formulated as follows:

- the welding process is stable if (($TI < 0.1$) and ($DCI < 0.1$) and ($TSI < 1.1$)), or (($0.3 < TI < 0.5$) and ($0.5 < DCI < 0.8$) and ($TSI < 0.2$);
- the welding process is stable enough if ($0.3 < TI < 0.5$) and ($0.3 < DCI < 0.5$) and ($TSI < 0.2$).

All numerical values of limits of the given parameters were obtained as a result of processing of expert estimates made by associates of the Crandfield University (Great Britain).

CONCLUSION

The welding process is called stable if deviation of its parameters from the mean values is not in excess of the specified level. The measure of stability of the welding process is deviation of its parameters from the mean values. The variance of a parameter, standard deviation or variation coefficient is taken as its deviation from the mean value.

The simplest way of evaluating stability of the GMAW process is to evaluate stability of its electric parameters. It is inexpedient to use variance, standard deviation or coefficient of variation of the welding current and arc voltage to evaluate stability of the process of pulse welding, modulated current welding and welding with metal transfer at periodic short circuits of the arc gap.

The set of indicators of the welding process stability depends on the welding method and character of transfer of the electrode metal into the weld pool. The set of the indicators of the welding process stability can be combined into one integrated stability indicator, allowing for the significance coefficient.

Stability of the welding process also depends on the welding consumables, welding equipment and welding parameters.

Therefore, based on ensuring the process stability, it is necessary to compare, e.g. welding consumables by using the same equipment and the same welding parameters. When investigating dependence of stability of the welding process on the welding equipment and parameters, it is necessary to keep to the similar conditions.

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