366. Calculation of optimal parameters of vibration electrode for arc welding

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Abstract. Manual and semi-automatic welding by vibration electrode (pulsing arc) is considered in the article. The advantages of welding by the pulsing arc are determined in comparison with welding by a constant arc. Using energy calculation by taking into account thermal balance at the vibration electrode stub, optimal parameters of modulated current, such as frequency and duration of electrical pulses, were established for different welding methods and regimes. Stabilized heat that is required for generating melting drops reduces the level of metal splash and improves formation of the weld.

Keywords: Welding process, vibration electrode, pulsing arc, pulse current, pulse frequencies, modulated current, thermal balance at the electrode stub.

Notation

F - Frequency drop of molten metal and pulse current
d_e - Electrode diameter
I_w, I_s, I_{ave}, I_{av} - Mean magnitude of welding current
I_i - Amplitude of the pulse current
τ_i - Pulse duration
τ_p - Pulse pause
τ, T_i - Pulse period
f_p, f, f_m - Frequency of the pulse current

Introduction

Arc welding is widely applied in practice. Gas-shielded metal-arc welding is frequently used, which operates in the environment of either active gases (MAG process) or inert gases (MIG process). Manual welding that uses flux-coated consumable electrode is referred to as MMA welding. Metal arc welding is the predominant type of welding used in practice. Now the fraction of metal, deposited by manual arc welding, is reduced because of more broad usage of the mechanized methods of welding. However, the manual welding by covered electrodes remains one of the most widespread types and is widely applied at assembly constructions. Under the forecasts, in near future the percentage of metal deposited by manual arc welding in industrially developed countries will be within the limits of 15-20 %, and in construction will make 85-90 % of total amount of welding work [1].

It is known that manual arc welding by covered electrodes is accompanied by fairly large losses of metal on splashing, evaporation and stubs ends (15-20 %), and considerable proportion of entire losses constitutes splashing molten metal (9-15 %) [2]. It is accompanied not only by loss, but also by the surface pollution of the welded metal (adhesion of drops). Stiffened sparks aggravate the exterior of a hardware product, and in some cases increase the probability of defect generation [3]. Therefore it is necessary to carry out surfaces clearing on the welded hardware products and for this purpose special tools, padding work breakdowns and energy are required. One of the most effective methods of splashing reduction during arc welding is application of the pulsed (modulated) current for reaching pulsing arc using vibration electrode. During current impulse the electrode fuse is quite fast. When current is paused electrode fuse is much slower. Thereby electrode vibration is obtained. Welding by vibration electrode solves many of other problems and allows improvement of quality of welded joints [4-9].

Advantage of welding by vibration electrode

At present vibration electrode (pulsing arc) is more frequently used in arc welding because it has a lot advantages in comparison with the usual arc. Main advantages are as follows [4]:

- the possibility to get stable welding process in vertical and overhead positions;
- the opportunity to take control of carrying of electrode metal;
- the ability to control thermal cycle of parts being welded;
- to avoid cracks;
- to lower the level of residual stresses and deformations.

It is known that in the case of arc welding by covered electrodes the time between transitions of the drops of metal can be 0.05-1.0 s and usually makes 0.1-0.5 s [1], i.e. real transition frequency of drops *F*=2-10 Hz. Using such pulse frequencies of a current it is possible to receive small but sufficiently powerful pulsations of the arc comparable with welding bath inertia. In the case of large volume of welding bath (large currents) for increasing power of the pulsing arc it is necessary to lower pulse frequency of the current up to 1 Hz or even less. Arc pulsations of sufficient power affect crystallization (callosity) of the welded material and there is a capability to control process of formation of the weld. As current pulse the arc increases, the quantity of molten electrode and base metal is magnified. At impulse pause the power of an arc is sharply reduced. This promotes acceleration of crystallization of the molten metal of welding bath with lowering of the quantity of molten metal. By changing parameters of the modulated current it is possible to operate crystallization speed of the weld metal, to change the volume and fluidity of the bath, to provide necessary penetration ability of the arc without perils to burn holes and capability of welding in different spatial positions [4].

The application of modulated current for welding of low-carbon high-strength steels allowed improvement of the formation of structure and properties [5] of welded joints and their resistance hardness to delayed destruction:

- contents of injurious diffusive hydrogen has decreased by 25 %;
- primary structure of the weld metal (up to 40 %) was crushed;
- service characteristics were increased up to 30 %;
- crack initiation was slowed considerably.

It is proved that the use of vibrated electrode partly improves the environment safety factor of the welding process. In this case the overflow energy of the arc and the evaporation of melting electrode materials is diminished. The experiments demonstrate that the intensity of aerosol evaporation is diminished when the welding is being carried out using modulated current [6]. The amount of health-harmful hard welding aerosol fraction containing noxious manganese can be considerably diminished.

Literature analysis revealed indisputable advantages and perspectives of the application of modulated current for welding by a vibration electrode. The calculation methods of optimal parameters of the modulated current for different welding parameters are provided below.

Calculations

For transition of high quality metal through an arc gap it is necessary to accomplish transfer of one drop of molten metal at the transport time of one current pulse, i.e. the frequency of transfer of drops should be equal to the frequency of the modulated (pulsed) current. Therefore pulse frequency F should be equal to the quotient from division of the consume volume of an electrode stick to the drop volume:

$$F = \frac{\pi r_e^2 V_l}{\frac{4}{3}\pi r_d^3}, \quad (1)$$

where r_e - electrode stick radius; V_l – linear speed of electrode fusing (burn-off rate); r_d - radius of molten metal drop.

For good welding process with small splashing it is desirable to receive small drops transfer of electrode metal, i.e. diameter of drops d_d must be less than the diameter of electrode rod d_e. On the other hand, excessively small drops will increase the frequency of their transition, demand adequate frequency of current pulse, and the power of arc pulsations will be insufficient in order to affect molten metal of a welding bath. Therefore, suppose that $d_d= 0{,}8d_e$. Considering, that $r_e=0.5d_e$ and $r_d=0.4d_e$ the formula (1) becomes:

$$F = 2.93\frac{V_l}{d_e}. \quad (2)$$

Electrode diameter d_e and mean magnitude of welding current I_w is selected depending on thickness S of welded metal from handbook data (Table 1).

Table1. Data of welding parameters (MMA process)

S, mm	0,5-2,5	1,0-3	1,5-5	3-10	6-20	10-30
d_e, mm	2	2,5	3	4	5	6
I_w, A	40-70	50-100	80-130	120-200	180-300	220-400

The wide scatter of welding currents is explained by the fact, that a welding in vertical and overhead positions the current magnitude smaller, and for welding of lap and tee joints is possible to apply the greater current, since in this case the hazard of leaky penetrations is smaller.

Linear speed of electrode fusing is equal to:

$$V_l = \frac{V_m}{S_e\rho} = \frac{4V_m}{\pi d_e^2\rho}, \quad (3)$$

where V_m - mass (quantitative) speed of electrode fusing; S_e - cross-sectional area of an electrode stick; ρ - the density of the steel (7.8 g/cm^3).

Mass speed of electrode fusing is:

$$V_m = \alpha_d I_w, \qquad (4)$$

where α_d - deposition coefficient (for electrodes УОНИ-13/45 α_d= 9.0 g/Ah [10]).

Inserting expression (4) into the equation (3) and taking into account, that ρ=7.8·10^{-3} g/mm^3 and α_d=2.5·10^{-3} g/As, we obtain:

$$V_l = \frac{0.408 I_w}{d_e^2}, \text{ mm/s}. \qquad (5)$$

Inserting expression (5) into the equation (2) the formula for pulse frequency calculation of the modulated current is:

$$F = \frac{1.2 I_w}{d_e^3}. \qquad (6)$$

Here the coefficient can vary slightly depending on the sizes of given drops of molten metal. The accomplished analysis showed good correlation with the literary data. For example, at welding current I_w=200 A (reverse polarity) for an electrode УОНИ-13/45 (d_e=4 mm) the duration of drops transitions is τ=187-350 ms, and their masses are within the limits of 88-136 mg [11]. The advisable pulse frequencies F vary from 1.7 Hz [5] up to 5 Hz [8]. According to this methodology F=3.75 Hz, τ=267 ms (τ=1/F), and mass of a drop (r_d=0.4d_e=1.6 mm) is equal 134 mg (actually smaller because of the losses on splashing and evaporation).

For the definition of the necessary durations of impulses τ_i of the modulated current we shall take an advantage of power calculation using thermal balance at the electrode stub:

$$Q_{fus} + Q_{ev} + Q_{h.ch} + Q_{ov.h} = Q_e + Q_{h.dr} + Q_{chem}, \qquad (7)$$

where values outlay of power Q are :

- Q_{fus}- fusion of the electrode;
- Q_{ev} - evaporation of metal;
- $Q_{h.ch}$ - heat interchange with environment;
- $Q_{ov.h}$ - overheating of drop metal;
- Q_e - heat generated by arc and flowing current at the electrode stub;
- $Q_{h.dr}$ - heating of a drop by flowing current;
- Q_{chem} - proceeding of chemical reactions.

The outlay metal evaporation power Q_{ev} and overheating of the drop metal of a $Q_{ov.h}$ together make about 40 % of all consumed energy [2,11], which can be taken into account accepting fusion process efficiency of a electrode to be η=0.6.

The outlay of power of interchange ($Q_{h.ch}$= 2.5-4.1 % of all used energy) practically is equal to incoming power of proceeding chemical reactions (Q_{chem}=3.5-3.8 % of all coming energy) [11]. These outlays of power counterbalance one another and they can be eliminated.

The outlay of power of drop heating by flowing current is relatively small ($Q_{h.dr}$=0.2-0.5 % from all coming energy [11]), and it can be eliminated.

At such assumptions it is possible to consider that Q_{fus}=Q_e. During passing of one current pulse the outlay of power Q_e is the sum of heats, exuded on the electrode stub by the arc Q_{arc} and a flowing current Q_i [10]. It is obvious, that:

$$Q_{fus} = Q_{arc} + Q_i. \qquad (8)$$

Indispensable energy for heating and fusion of one molten metal drop with considering of losses on evaporation and overheating of the drop is determined:

$$Q_{fus} = V\rho(ct + \lambda)\eta^{-1}, \qquad (9)$$

where V – the volume of molten metal drop (r_d=0.4d_e); ρ – the density of steel (7.8·10^{-3} g/mm^3); c - specific heat capacity (for weigh unit) of molten metal (0.724 J/(g·K) [10]); t - mean temperature of molten metal drop (2600 K [10]); λ - specific fusion heat of a steel (272 J/g); η - the heat efficiency of electrode fusion (0.6).

The outlay of power of fusion one drop metal Q_{fus} for manual arc welding (MMA) and different diameters of electrodes d_e are presented in Table 2. This data is similar with results obtained by A. Erochin [11].

The quantity of heat provided up to the stub of an electrode by an arc Q_{arc} (reverse polarity) as concerns the effect of single current impulse practically is equal to exuded heat on anode in time τ:

$$Q_{arc} = \int_0^{\tau} (U_a + \varphi) i(t) dt, \qquad (10)$$

where U_a – anodic voltage (4V [12]); φ - output potential of an electron from the anode (4.18 V); $i(t)$ - the function of current impulse change.

The quantity of heat Qi, exuded on the stub of an electrode by a flowing current of one impulse is equal to:

$$Q_i = \int_0^{\tau} i^2(t) r_s(t) dt, \qquad (11)$$

where r_s - electric resistance of the electrode stub.

It is known that:

$$r_s = \frac{l_s \rho_s}{\pi r_e^2}, \qquad (12)$$

where l_s - the length of effective heating of the electrode stub (≈5 mm); ρ_s - mean specific resistance of the electrode stub (≈$3\cdot10^{-4}$ Ω·mm); πr^2_e - cross-sectional area of the electrode.

Considering, that the length of effective heating l_s and mean specific resistance ρ_s of stub the electrode are constants, the expression (11) will be converted:

$$Q_i = \frac{l_s \rho_s}{\pi r_e^2} \int_0^{\tau} i^2(t)dt, \quad (13)$$

Inserting magnitudes Q_{arc} and Q_i into the equation of thermal balance (8), we obtain the following:

$$Q_{fus} = 8.18\int_0^{\tau} i(t)dt + \frac{l_s \rho_s}{\pi r_e^2} \int_0^{\tau} i^2(t)dt \cdot \quad (14)$$

In the obtained expression unknown magnitudes are pulse duration τ_i and the function current pulse $i(t)$ change. However, it is possible to assign the form and amplitude of the pulse current I_i subjected to a particular welding schedule. In the case of a rectangular pulse current, according to the formula (14), the necessary pulse duration τ_i it is possible to determine by means of the following expression:

$$\tau_i = \frac{Q_{fus}}{I_i\left(8.18 + \frac{I_i l_s \rho_s}{\pi r_e^2}\right)} \quad (15)$$

Using the last expression optimal pulse durations τ_i and amplitude I_i are determined at different welding parameters for manual arc welding by the covered electrodes (MMA) (Table 2).

Table 2. Parameters of the modulated current (MMA process)

d_e, mm	Q_{fus}, J	I_w, A	F, Hz	I_i, A	τ_i, ms
2	60,1	50	7,50	100	73
		70	10,50	140	52
2,5	117	60	4,61	120	119
		90	6,91	180	79
3	203	90	4,00	180	137
		120	5,33	240	103
4	480	130	2,44	260	224
		180	3,38	360	162
5	938	190	1,82	380	300
		260	2,50	520	219
6	1622	260	1,44	520	379
		350	1,94	700	281

Analogously, optimal pulse parameters determined for gas-shielded metal-arc welding using active gases (MAG) (Table 3).

Table3. Parameters of pulses (MAG process)

d_e, mm	I_s, A	$V_v\cdot10^{-2}$, m/s	f_p, Hz	Q, J	I_i, A	τ, ms
1.0	100	6.0	90	6.7	360	1.81
1.0	150	10.0	150	7.5	360	2.05
1.0	200	15.0	225	7.5	360	2.04
1.2	150	7.5	94	12.1	420	2.88
1.2	200	11.3	141	12.1	420	2.87
1.2	250	15.8	198	11.3	420	2.74
1.4	200	8.5	91	17.6	500	3.66
1.4	250	11.5	123	17.6	500	3.61
1.4	300	15.0	161	16.7	500	3.46

At initial arc excitation, the development of torch of plasma occurs at speed of about 10 km/s. It specifies explosive character of electrons issue. After the beginning of arc starting speed of development of plasma decreases up to 200m/s, according of Institute of Physics (Lithuania). For manual arc welding (MMA) the average length of an arc is ~3mm and its width is approximately equal to a diameter of the electrode. Proceeding from these data we conclude, that it is enough 10μs for development of a welding arc. At such and greater pulse duration of a current there is a stable arc excitation. Parameters of high-frequency pulses [9] are defined in Table 4.

Table 4. Parameters of high-frequency pulses (MMA process)

f, kHz	20	22	24	26	28	30
T, μs	50	45	42	38	36	33
t_i, μs	11	11	11	11	11	11
t_p, μs	39	34	31	27	25	22
I_{ave}, A	130	130	130	130	130	130
Q, J	4.5	4.1	3.8	3.5	3.2	3.0
I_i, A	591	537	492	455	422	394

The range of average frequency current pulses must coincide with the liquid metal drops traffic frequency (30-200 Hz). In this way every liquid metal drop gets one current pulse and this makes it easier to transfer. This way fully controlled liquid electrode metal transferring and pulsed current welding is obtained [9]. Nowadays power sources may form the current having not only any frequency needed but can change the pulse pause τ_p, duration τ_i, amplitude I_i and basic current I_p quantities.

During the pauses of impulses τ_p usually will use a small base current (I_p≈50 A [5]) is used for the support arc burning. In this case average welding current I_{av} is equal to:

$$I_{av} = \frac{I_p \tau_p + I_i \tau_i}{T_i}, \quad (16)$$

where T_i - the period of impulses ($T_i = \tau_i + \tau_p$).

As the result pulsed current frequency f_m is changed as shown in Table 5.

Table 5. Parameters of the pulses current (MMA process)

I_{av}, A	220	220	220	220	220
τ_i, s	0,01	0,01	0,01	0,01	0,01
I_p, A	50	50	50	50	50
τ_p, A	0,01	0,015	0,02	0,025	0,03
I_i, A	390	475	566	644	730
f_m,Hz	100	67	50	40	33

The use of the calculated parameters of the modulated current will allow stabilization of optimal heat quantities that are necessary for making liquid drops, reducing splashing of the metal and improving quality of weld formation.

Conclusions

1. Obtaining pulsing arc and vibration electrode by using of the pulsed current. Performed literature analysis has revealed obvious advantages of application of the vibration electrode and importance of estimation of its optimal parameters for welding by pulsed arc.

2. For manual arc welding by the covered electrodes the indispensable modulated current pulses frequencies are estimated. They are directly proportional to the average magnitude of arc current and are inversely proportional to the third power of the used electrode diameter (F=1.2I_w /d^3_e).

3. The analysis of heat at the electrode stub at single current impulse gives: the indispensable energies for fusion of drops of metal are considered as heats, exuded on the electrode stub by arc and flowing current. This allowed to assign optimal parameters of the modulated current for different welding methods and regimes.

References

[1] **Fedko V. T., Cipaliuk A. S.** Fusion and transition of electrode metal for arc welding by the covered electrodes. – Welding manufacturing. - Moscow, 2003, No2, p. 3–10. (In Russia).

[2] **Erochin A. A.** Fundamental of fusion welding. – Moscow: Mechanical engineering, 1973. – 448 p. (In Russia).

[3] **Akulov A. I., Belcuk G. A., Demjancev V. P.** Technology and equipmet for fusion welding. - Moscow: Mechanical engineering, 1977. – 432 p. (In Russia).

[4] **Vagner F. A.** Equipment and welding methods by pulsing arc. - Moscow: Energy, 1980. - 118 p. (In Russia).

[5] **Michoduj L. I.**, **Pozniakov V. D., Denisenko A. V.** Current modulation influence on low carbon high-proof steels welds properties, given manual arc welding. – Automatic welding. - Kiev, 1999, No4, p. 13 - 18. (In Russia).

[6] **Levcenko O. G.** Forming of aerosols while welding with modulated current in carbon dioxide. – Automatic welding. - Kiev, 2000, No8, p. 48-50. (In Russia).

[7] **Mazel A. G., Dediuch R. I.** Parameters of the modulated current influence on fusion electrode and depth fusion in manual arc welding. – Welding manufacturing. - Moscow, 1976, No4, c. 9-10. (In Russia).

[8] **Dediuch R. I., Azarov N. A., Mazel A. G.** Current modulation influence on weld formation conditions in manual arc welding and in electrodes covered from up to down. - Automatic welding. - Kiev, 1988, No7, p. 24-27. (In Russia).

[9] **Ščemeliovas J.** Welding Pulse Current Influence on Weld Seam Formation. – Mechanika. – Kaunas: Technologija, 2003, No6, p. 62–65.

[10] **Bagrianskij K. B., Dobrotina Z. A., Chrenov K. K.** Theory of welding processes. – Kiev: High school, 1976. – 424 p. (In Russia).

[11] **Erochin A. A.** Kinetics of metalurgical process for arc welding. – Moscow: Mechanical engineering, 1964. – 256 p. (In Russia).

[12] **Leskov G. I.** Electric welding arc. - Moscow: Mechanical engineering, 1970. – 335 p. (In Russia).

[13] **Ščemeliovas J.** Determination of pulse current optimal parameters for manual arc welding. – Mechanika. – Kaunas: Technologija, 2005, No1, p. 66–69.