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OPTIMIZATION OF THE PULSED CURRENT WAVEFORM AND PARAMETERS IN HFPC TIG WELDING

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ABSTRACT

Experimental studies have shown that high-frequency pulsed modulation of welding current allows for an increase in penetration capacity of the welding process with tungsten electrode. This effect is attributed to intensified convective flows in the weld pool, excited by a high-frequency electromagnetic field. The article examines the problem of determining the shape and parameters of welding current pulses that maximizes the force exerted by the modulated current on the weld pool metal. The square of the effective value of the welding current is taken as an integral measure of the force action of the electromagnetic field on the molten metal of the weld pool. The difference between the squares of the effective and average values of the modulated current, which characterizes the excess of the force action of the arc with pulsed current modulation over the force action of the direct current arc, is taken as a criterion for optimizing the shape of the current pulse. The problem of variational calculus on finding such a current pulse shape, at which the maximum of the specified difference is achieved, is solved. Two optimization methods are considered: at a given modulation amplitude and at a given average value of the modulated current. It is rigorously shown mathematically that in the first case the optimal pulse shape is a square wave, in the second case — a rectangular current pulse, the duty cycle and amplitude of which are determined by the value of the maximum current of the welding generator. The optimization of parameters of current pulses of trapezoidal and triangular shapes generated by existing welding current generators has been carried out. The proposed theory can serve as a guideline in the development of effective pulse current generators, as well as in the design the modes of the tungsten inert gas welding process with high-frequency pulsed modulation of welding current in order to increase the penetration depth and improve welding productivity.

KEYWORDS: TIG welding, arc plasma, weld pool, electromagnetic force, direct current, pulsed current, mean and RMS values, wave form, duty cycle, amplitude, frequency

INTRODUCTION

In modern industrial production, the tungsten inert gas arc welding (TIG process) is used in the manufacture of critical structures in various industries. In order to increase the penetration ability of TIG welding, various activation methods are applied: the use of various shielding gases and their mixtures [1, 2], the application of special activating fluxes to the surface of the welded metal [3, 4], TIG welding in the keyhole mode (K-TIG process) [5], high-frequency pulse (HFP) modulation of the welding current [6–10]. Figure 1 shows the sections of welds obtained during TIG welding of a 5 mm thick plate made of 1.4301 (AISA 304) stainless steel using direct and modulated currents. Experimental conditions were as follows: arc length of 1.5 mm; direct current of 150 A, current modulation frequency of 6 kHz, average modulated current of 153 A, trapezoidal pulse shape with front duration of 55 μs; base current of 44 A, modulated current amplitude of 204 A.

With minor deviations of the average value of the modulated current and the average arc power from the corresponding parameters of direct current, the depth of penetration and the volume of molten metal during TIG welding with HFP modulation of the welding current (HFP TIG process) are noticeably greater than during TIG welding with direct current. A similar effect of increased penetration capacity of the HFP TIG process was also experimentally discovered earlier in works [7, 8, 10]. This effect can be explained by the fact that the effective value of the modulated current exceeds the direct current by 30 %.

The efficiency of high-frequency pulsed modulation of the arc current as a means of increasing the depth of penetration in TIG welding depends on such parameters as the shape of the current pulse, the duty cycle, the amplitude and the modulation frequency. With the optimal choice of these parameters, the force action of the electromagnetic field of the current on the metal of the weld pool is increased, the convective heat exchange in the molten metal is intensified, and thereby the penetration capacity of the arc with

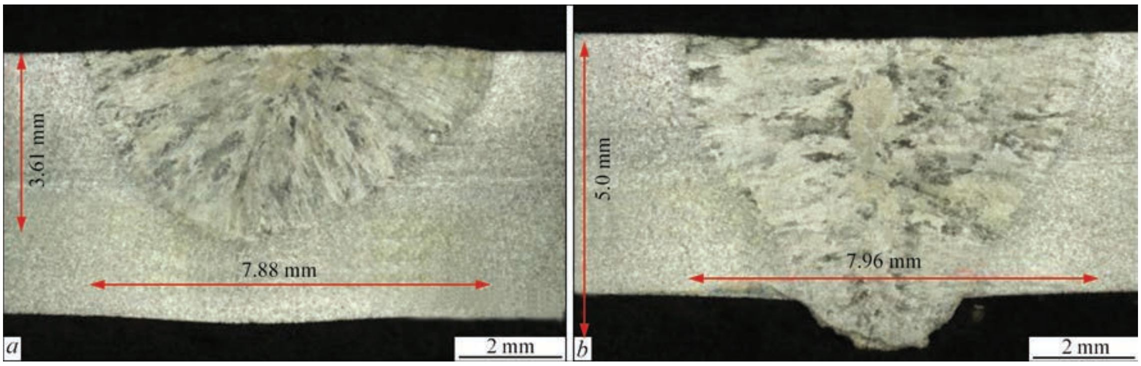

Figure 1. Shapes of welds in TIG welding. *a* — with direct current; *b* — with HFP modulation of the welding current

a refractory cathode increases. The purpose of this work is to determine the shape and parameters of the welding current pulses that are optimal according to the criterion of the maximum force action of the modulated current on the metal of the weld pool.

OPTIMIZATION OF THE SHAPE AND PARAMETERS OF CURRENT PULSES

We will assume that the modulated welding current $I(t)$ is unipolar ($I(t \geq 0)$ and periodically changing in time t with a period T. The average I_{av} and effective I_{eff} values of current are determined as follows: $I_{av} = \langle I(t) \rangle; I_{eff} = \sqrt{\langle I^2(t) \rangle}$, where $\langle f(t) \rangle = \frac{1}{T}\int_0^T f(t)dt$ is the integral average value of the periodic function $f(t)$ on the segment $t \in [0; T]$.

In work [11] it is shown that during TIG welding with HFP current modulation, the volume density of the electromagnetic force exciting the magnetohydrodynamics of the weld pool depends on the averaged value of the square of the current $\bar{I}^2(r, z)$ over one modulation period, flowing within a circle of radius r in an arbitrary axial section z of the pool. The greater the effective value of the modulated welding current I_{eff}, the greater its distributed characteristic $\bar{I}^2(r, z)$ and, accordingly, the greater the force effect of the modulated welding current on the molten metal. Therefore, as an integral measure of such effect, we will take the square of the effective value of the welding current. The force effect of the modulated current arc on the metal of the weld pool will be compared with the force effect of the direct current arc, equal in magnitude to the average value I_{av} of the modulated current.

Let $I_1 < I(t) < I^2$, $t \in [0; T]$, where I_1 is the base value of the current; $A = I_2 - I_1$ is the amplitude, T is the modulation period. On the segment [0; 1] of dimensionless time $\tau = \frac{t}{T}$, the law of current change can be written as:

$$I(\tau) = I_1 + A\eta(\tau), \quad (1)$$

where $\eta(\tau)$ is the normalized shape of the current pulse.

We will consider in the general case, the set M of Lebesgue measurable functions as functions $\eta(\tau)$, such that $0 \leq \eta(\tau) \leq 1$, $\tau \in [0; 1]$. For the squares of the effective and average values of the modulated current, the following expressions hold:

$$\begin{aligned} I_{eff}^2 &= I_1^2 + 2AI_1\langle \eta(\tau) \rangle + A^2 \langle \eta^2(\tau) \rangle; \\ I_{av}^2 &= I_1^2 + 2AI_1\langle \eta(\tau) \rangle + A^2 \langle \eta(\tau) \rangle^2. \end{aligned} \quad (2)$$

Subtracting the right- and left-hand parts of equalities (2), we obtain

$$\Delta = I_{eff}^2 - I_{av}^2 = A^2\left(\langle \eta^2(\tau) \rangle - \langle \eta(\tau) \rangle^2\right). \quad (3)$$

Consider the problem of finding the normalized pulse shape $\eta(\tau) \in$ M, which provides $\max\limits_{\eta(\tau)\in M} \Delta$. Two formulations of such a problem are possible. In the first one we assume that current pulses (1) are generated by normalized shapes of $\eta(\tau)$, as long as amplitude A remains constant and independent on the pulse shape $\eta(\tau)$. In this case, it follows from (3) that the optimal shape of the current pulse $\eta(\tau)$ delivers a maximum to the functional $\Phi[\eta(\tau)] = \int_0^1 \eta^2(\tau)d\tau - \left(\int_0^1 \eta(\tau)d\tau\right)^2$.

The following assertion holds

THEOREM

Let $\eta(\tau) \in$ M be the normalized shape of the current pulse such that for all $\tau \in [0; 1]$ the following inequalities hold $0 \leq \eta(\tau) \leq 1$. Then, $\Phi[\eta(\tau)] \leq \frac{1}{4}$, and equality is achieved if and only if there exists measurable set $B \subset [0; 1]$, $\mu(B) = \frac{1}{2}$, where μ is the Lebesgue measure on a straight line, such that the following equalities hold for almost all $\tau \in [0; 1]$

$$\eta(\tau) = \begin{cases} 1, & \tau \in B; \\ 0, & \tau \notin B. \end{cases} \quad (4)$$

PROOF

As long as $0 \le \eta(\tau) \le 1$, the inequality $\langle\eta^2(\tau)\rangle \le \langle\eta(\tau)\rangle$ holds. Hence, $\Phi[\eta(\tau)] \le \langle\eta(\tau)\rangle - \langle\eta(\tau)\rangle^2$. Function $\langle\eta(\tau)\rangle - \langle\eta(\tau)\rangle^2$ reaches its maximum at $\left\langle\eta(\tau)\right\rangle = \frac{1}{2}$, and this maximum is equal to $\frac{1}{4}$. Thus, $\Phi\left[\eta(\tau)\right] \le \frac{1}{4}$. In the latter condition, the equality is achieved if and only if $\left\langle\eta(\tau)\right\rangle = \left\langle\eta^2(\tau)\right\rangle = \frac{1}{2}$. Condition $\langle\eta(\tau)\rangle = \langle\eta^2(\tau)\rangle$ implies that for almost all $\tau \in [0;\ 1]$ the following equality holds: $\eta(\tau) = \eta^2(\tau)$. Hence, $\eta(\tau) = 0$ or $\eta(\tau) = 1$ for almost all $\tau \in [0;\ 1]$. Let $B \subset [0;\ 1]$ be a set of such values of $\tau \in [0;\ 1]$ that $\eta(\tau) = 1$. Now we have $\left\langle\eta(\tau)\right\rangle = \int_0^1 \eta(\tau)\,d\tau = \mu(B)$. Taking into account the equality $\left\langle\eta(\tau)\right\rangle = \frac{1}{2}$, we obtain $\mu(B) = \frac{1}{2}$, i.e. equalities (4) are true. It suffices to note that equality $\Phi\left[\eta(\tau)\right] = \frac{1}{4}$ is valid for the found function $\eta(\tau)$. The theorem is proved.

The considered problem about the maximum of functional $\Phi\ [\eta(\tau)]$ in the class of Lebesgue measurable functions has a non-unique solution, and there are infinitely many equivalent functions $\eta(\tau)$ such that the sets of points of $[0;1]$ for which $\eta(\tau) = 0$ and $\eta(\tau) = 1$, have the same Lebesgue measure $\mu(B) = \left\langle\eta(\tau)\right\rangle = \frac{1}{2}$. In practical applications of pulsed modulation of welding current, function $\eta(\tau)$ in the form of a unit jump (rectangular pulses in the form of a square wave) is of greatest interest

$$\eta(\tau) = \begin{cases} 1, & 0 \le \tau < \frac{1}{2}; \\ 0, & \frac{1}{2} \le \tau \le 1; \end{cases} \quad \Delta_1 = \frac{1}{4}A^2. \tag{5}$$

The optimum shape of current pulse (5), determined at fixed modulation amplitude A, leaves arbitrariness in the average and effective current values. To eliminate it, we must additionally set another current parameter, for example, value of base current I_1. In this case, $I_{av} = I_1 + \frac{1}{2}A$, $I_{eff} = \sqrt{I_{av}^2 + \frac{1}{4}A^2}$, and the expression for Δ_1 can be written in the following form $\Delta_1 = \widehat{I}_{av}^2$, where $\widehat{I}_{av} = I_{av} - I_1$.

Let us consider another possibility of finding $\max\limits_{\eta(\tau)\in M} \Delta = \Delta_2$ without the assumption that current modulation amplitude A is fixed. Instead, in (1) we will assume that current pulses $I = I(\tau)$ are generated, provided the current value $\widehat{I}_{av}$ is kept constant at all $\eta(\tau) \in M$. If I_1 is given this method of current pulse shape optimization is convenient for assessment of the effectiveness of force action of modulated current, compared to the impact of direct current equal to I_{av}.

With this approach of optimization, the current amplitude becomes dependent on pulse shape and, as it follows from (1), this dependence has the form of $A\left[\eta(\tau)\right] = \frac{\widehat{I}_{av}}{\left\langle\eta(\tau)\right\rangle}$. Then, $\Delta = \widehat{I}_{av}^2 \frac{\left\langle\eta^2(\tau)\right\rangle - \left\langle\eta(\tau)\right\rangle^2}{\left\langle\eta(\tau)\right\rangle^2}$ and the problem arises of finding the maximum of functional $F\left[\eta(\tau)\right] = \left[\int_0^1 \eta^2(\tau)\,d\tau \Big/ \left(\int_0^1 \eta(\tau)\,d\tau\right)^2 - 1\right]$ in the class of functions $\eta(\tau) \in M$.

We denote by $M_\delta \subset M$ the subset of such functions $\eta(\tau)_\delta \in M$, for which $\langle\eta_\delta(\tau)\rangle = \delta$, where $\delta \in [0;\ 1]$ is a certain fixed parameter. It is obvious that $\bigcup\limits_{\delta\in[0;1]} M_\delta = M$. Similarly to the proof of the theorem, the estimate $F\left[\eta_\delta(\tau)\right] \le \frac{1}{\delta} - 1$ is valid, and the equality holds for those and only for those functions $\eta_\delta(\tau) \in M_\delta$ for which a measurable set $B_\delta \subset [0;\ 1]$, $\mu(B_\delta) = \delta$ exists, such that equalities (4) hold for almost all $\tau \in [0;\ 1]$. For example, function

$$\eta_\delta(\tau) = \begin{cases} 1, & 0 \le \tau < \delta; \\ 0, & \delta \le \tau \le 1, \end{cases} \tag{6}$$

delivers maximum to functional $F[\eta_\delta(\tau)]$ and defines the pulses of a rectangular shape with duty cycle δ.

In welding generators, the maximum possible current is limited by the maximum current of the generator. In this connection, we will further assume $A[\eta(\tau)] \le A_{max}$. This condition, given the selected value $\widehat{I}_{av}$, imposes a lower limit on $\langle\eta(\tau)\rangle$, i.e.: $\left\langle\eta(\tau)\right\rangle \ge \frac{\widehat{I}_{av}}{A_{max}} = \delta_{min}$. Thus for $\eta_\delta(\tau) \in M_\delta$ inequality $\delta \ge \delta_{min}$ holds, and, therefore, $\max\limits_{\eta_\delta\in M_\delta} F\left[\eta_\delta(\tau)\right]$ is achieved on functions $\eta_\delta(\tau) \in M_\delta$ when $\delta \ge \delta_{min}$, and this maximum is equal to $\frac{1}{\delta_{min}} - 1$. Then, for maximum difference of the squares of effective and average values of modulated current in the second optimization method, we have

Table 1. Optimal parameters of current modulation by rectangular pulses at different (set) values of $\hat{I}_{av}$

$\hat{I}_{av}$, A	50	100	150	200	250	300	350	400
δ_{min}	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
I_{eff}, A	158	224	274	316	354	387	418	447
Δ^2, 10^3 A^2	22.5	40.0	52.5	60.0	62.5	60.0	52.5	40.0

$$\Delta_2 = \hat{I}_{av}^2\left(\frac{1}{\delta_{min}} - 1\right). \qquad (7)$$

It means that the optimum method of current modulation at the set values of average I_{av} and base I_1 current is modulation by rectangular pulses with minimum possible duty cycle δ_{min} for the set value of $\hat{I}_{av}$ at the selected value of A_{max}. It follows from the alternative form of writing expression (7) $\Delta_2 = \hat{I}_{av}\left(A_{max} - \hat{I}_{av}\right)$ that the right-hand side of this equality has a maximum, which is achieved with $\hat{I}_{av} = \frac{1}{2}A_{max}$, $\delta_{min} = 0.5$ that corresponds to pulses in the form of a meander (5).

Let us give numerical estimates of optimal parameters of rectangular current pulses, assuming $A_{max} = 500$ A (maximum power source current in [8]). Table 1 gives the calculated data on the change of the minimum possible value of duty cycle δ_{min}, effective current value I_{eff}(at $I_1 = 0$), as well as maximum difference Δ_2 of the squares of the effective and average current values, depending on the value of $\hat{I}_{av}$.

Figure 2 shows a comparison of two methods of optimization of the shape and parameters of current pulses, considered above: 1) at fixed modulation amplitude $A \le A_{max} = 500$ A (dashed curve); 2) at fixed current $\hat{I}_{av}$ and given above maximum amplitude value (solid curve). Note that in the first case at $\hat{I}_{av} > \frac{1}{2}A_{max}$, current modulation amplitude A exceeds the accepted restriction, therefore we will perform

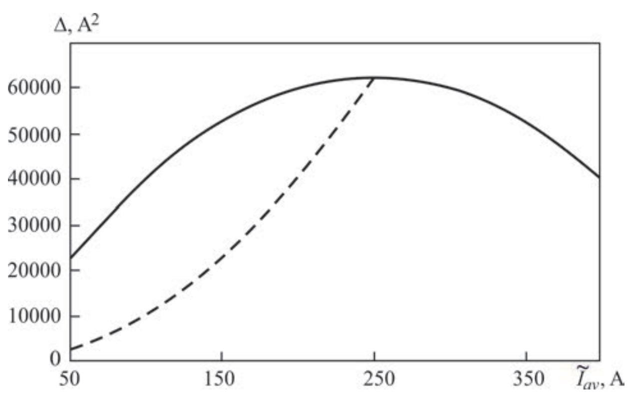

Figure 2. Change of (dashed curve) and (solid curve), depending on at $A_{max} = 500$ A

comparison of the above optimization methods in the domain of $\hat{I}_{av} \le 250$ A.

It follows from the calculated data presented in this Figure that excess of force action of modulated current over the impact of direct current, equal to average value of modulated current, is significantly higher with the second method of optimization, and both the variants become equivalent only in the point of maximum ($\hat{I}_{av} = 250$ A).

As it follows from the definition of $\hat{I}_{av}$ $I_{av} - I_1$, increase of base current at constant average value of current leads to decrease of $\hat{I}_{av}$ and to decrease of Δ_1, Δ_2 in the domain of $\hat{I}_{av} \le 250$ A, respectively (see Figure 2), thus lowering the effectiveness of force impact of modulated current.

OPTIMIZATION OF PARAMETERS OF TRAPEZOIDAL AND TRIANGULAR CURRENT PULSES

The creation of arc power sources with high-frequency current modulation, which are capable of generating rectangular pulses in a wide frequency range, is a complex engineering task [8, 12]. In this case, the rate of current rise/fall at the pulse fronts that can actually be achieved in the welding circuit is of the order of 20–50 A/μs, which, for example, with a current modulation amplitude of 500 A will correspond to a total front duration of the order of 20–50 μs. Therefore, for practical applications, it is of interest to consider current pulses of trapezoidal and, as a special case, triangular shape, which can potentially be implemented using existing welding power sources for TIG welding with HFP current modulation.

Let us first consider a trapezoidal current pulse, shown in Figure 3, with the following time parameters: t_1 — duration of the leading edge; $t_2 - t_1$ — duration of the "peak" of the pulse;$t_3 - t_2$ — duration of the trailing edge; t_3 — pulse duration; $T - t_3$ — pause duration.

We will put dimensionless parameters $\tau_1 = \frac{t_1}{T}$, $\tau_2 = \frac{t_2}{T}$, $\tau_3 = \frac{t_3}{T}$ into correspondence with the dimensional time parameters of the pulse and will introduce the following designations: $\tau_{21} = \tau_2 - \tau_1$ — dimensionless duration of the "peak"; $\tau_f = \tau_1 + \tau_3 - \tau_2$ — total dimensionless duration of the pulse fronts.

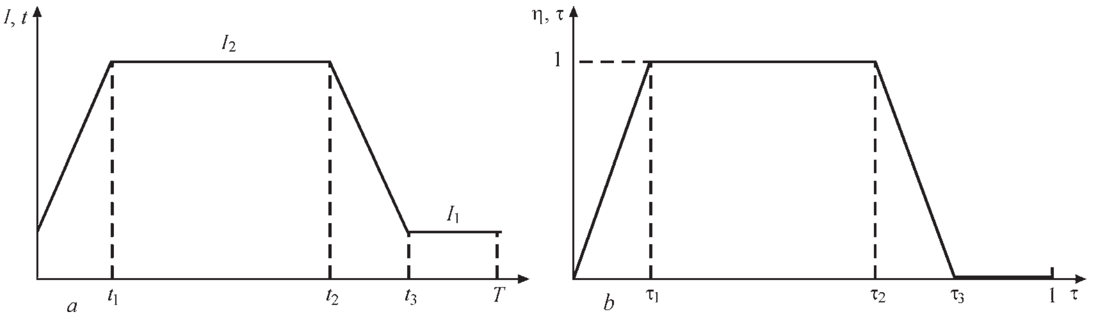

Figure 3. Trapezoidal current pulse (*a*) and its normalized form (*b*)

For the normalized form of a trapezoidal current pulse it is easy to obtain: $\left\langle \eta(\tau) \right\rangle = \tau_{21} + \frac{\tau_f}{2}$; $\left\langle \eta^2(\tau) \right\rangle = \tau_{21} + \frac{\tau_f}{3}$. These expressions depend only on the total dimensionless duration of the fronts. As before, we will consider two options for optimizing the pulse parameters.

Let us first assume that the trapezoidal current pulses are generated at fixed modulation amplitude A. Then, $\Phi(\tau_{21}, \tau_f) = \tau_{21} + \frac{\tau_f}{3} - \left((\tau_{21} + \frac{\tau_f}{2})^2 \right)$ function of dimensioless time parameters τ_{21}, τ_f corresponds to $\Phi[\eta(\tau)]$ functional. For a given value of τ_f, which is determined by the characteristics of the power source, $\max\limits_{\tau_{21}} \Phi(\tau_{21}, \tau_f) = \frac{1}{4} - \frac{\tau_f}{6}$ is achieved at

$$\tau_{21} = \frac{1}{2}(1 - \tau_f). \tag{8}$$

The maximum excess of the force action of a trapezoidal pulse over the force action of a direct welding current equal to I_{av} is determined by the value

$$\Delta_1 = \frac{A^2}{4}\left(1 - \frac{2}{3}\tau_f\right). \tag{9}$$

Note that for $\tau_f = 0$ (rectangular pulses) formula (9) corresponds to (5).

A triangular pulse is a special case of a trapezoidal pulse. In the expressions for $\langle\eta(\tau)\rangle$, $\langle\eta^2(\tau)\rangle$ we set $\tau_{21} = 0$, and we will identify τ_f with the duration of the triangular pulse. As a result we get: $\Phi(\tau_f) = \frac{1}{3}\tau_f - \frac{1}{4}\tau_f^2$. Analyzing this function for the extremum, we find that $\max\limits_{\tau_f} \Phi(\tau_f) = \frac{1}{9}$ is reached at $\tau_f = \frac{2}{3}$.

This means that a triangular current pulse is optimal if two-thirds of the period are taken by the pulse itself (leading and trailing edges), and one-third is the pause. The maximum excess of the force action of such a pulse over the force action of a direct current equal to $\widehat{I}_{av}$, is determined by the value

$$\Delta_1 = \frac{A^2}{9}. \tag{10}$$

Let us now assume that the trapezoidal current pulses are generated at fixed values of I_{av} and I_1, i.e. the value of $\widehat{I}_{av}$ is kept constant, and let us accept the constraint of $A \le A_{\max}$. Similarly to what was done in Section 1, it can be shown that for trapezoidal pulses $\max\left(I_{eff}^2 - I_{av}^2\right)$ is achieved at the minimum possible duty cycle $\delta_{\min} = \frac{av}{\max} + -\tau$ and is

$$\Delta_2 = \widehat{I}_{av}^2 \left[\frac{\delta_{\min} - 2\tau_f/3}{\left(\delta_{\min} - \tau_f/2\right)^2} - 1 \right].$$

Table 2. Optimal parameters of current modulation by trapezoidal and triangular pulses at different values of $\widehat{I}_{av}$

$\widehat{I}_{av}$, A		50	100	150	200	250	300	350
Trapezoidal pulses	$\delta_{\min}$	0.25	0.35	0.45	0.55	0.65	0.75	0.85
	I_{eff}, A	112	194	250	296	332	371	403
	Δ_2, 10^3 A^2	10.0	27.5	40.0	47.5	50.0	47.5	40.0
Triangular pulses	$\delta_{\min}$	0.2	0.4	0.6	0.8	1.0	–	–
	I_{eff}, A	129	180	224	258	289	–	–
	Δ_2, 10^3 A^2	14.17	22.33	27.50	26.67	20.83	–	–

Table 3. Optimal parameters of rectangular, trapezoidal and triangular current pulses for two optimization methods.

Current pulse shape	A = const		$\widehat{I}_{av}$ = const, $A \le A_{\max}$	
	δ	Δ_1	δ	Δ_2
Rectangular pulses	$\frac{1}{2}$	$\frac{1}{4}A^2$	$\frac{\widehat{I}_{av}}{A_{\max}}$	$\widehat{I}_{av}^2\left(\frac{1}{\delta}-1\right)$
Trapezoidal pulses	$\frac{1}{2}(1+\tau_f)$	$\frac{A^2}{4}\left(1-\frac{2}{3}\tau_f\right)$	$\frac{\widehat{I}_{av}}{A_{\max}}+\frac{1}{2}\tau_f$	$\widehat{I}_{av}^2\left[\frac{\delta-2\tau_f/3}{\left(\delta-\tau_f/2\right)^2}-1\right]$
Triangular pulses	$\frac{2}{3}$	$\frac{A^2}{9}$	$\frac{2\widehat{I}_{av}}{A_{\max}}$	$\widehat{I}_{av}^2\left[\frac{4}{3\delta}-1\right]$

At $\tau_f = 0$, the resulting expression coincides with formula (8) for rectangular pulses. In the case of triangular pulses, the expressions for Δ_2 and $\Delta_{\min}$ take the form of

$$\Delta_2 = \widehat{I}_{av}^2\left[\frac{4}{3\delta_{\min}}-1\right], \delta_{\min} = \frac{2\widehat{I}_{av}}{A_{\max}}.$$

Table 2 shows the quantitative characteristics of the optimal parameters of trapezoidal and triangular current pulses, calculated for $A_{\max}$ = 500 A, $I_1 = 0, \tau f = 0.3$.

The theory presented remains valid for current pulses whose normalized form does not depend on the modulation frequency (isomorphic pulses). The force effect of modulated current with non-isomorphic trapezoidal pulses (for example, with a fixed front duration) decreases with increasing modulation frequency.

CONCLUSIONS

1. In TIG welding, the difference between the squares of the effective and average values of the modulated current can be taken as an approximate measure of the excess of the force effect of the modulated welding current over the effect of direct current. The maximum of this difference serves as a criterion for optimizing the shape of the welding current pulses, ensuring the maximum force effect of the modulated current on the metal of the weld pool and, as a consequence, increasing the penetration capacity of the arc in TIG welding with high-frequency pulse current modulation.

2. The optimal shapes and parameters of welding current pulses defined in Section 1 for the general case of functions $\eta(\tau) \in L_1(0.1)$ form equivalence classes in which the seminorms of the elements included in them coincide. The mean value $\langle\eta(\tau)\rangle$ of the normalized pulse shape, which is equal to 0.5 for the conditions of the theorem, acts as $\|\eta\|$. In the equivalence class with $\langle\eta(\tau)\rangle = \frac{1}{2}$, in addition to square wave pulses with a frequency of F, it is possible to consider options for modulating the current with a finite number of subpulses such that their total relative duration is equal to 0.5, for example, rectangular pulses with frequencies nF, where $n > 1$ is an integer. Similarly, in the second optimization method, the value $\langle\eta(\tau)\rangle = \delta_{\min}$ can be achieved by generating a finite number of subpulses whose total relative duration is equal to $\delta_{\min}$. Such options are indistinguishable from the point of view of the considered integral criterion of force impact $I_{eff}^2 - I_{av}^2$.

3. Expressions for the parameters of optimal rectangular, trapezoidal and triangular current pulses are summarized in Table 3.

These parameters can serve as a guideline for designing welding modes, as well as for developing more advanced pulse current generators capable of providing increased penetration capacity of the HF TIG process.

4. When conducting experimental studies of the penetration capacity of modulated current and unambiguous interpretation of their results, it is important to use pulse current generators stabilized by a normalized pulse shape in a wide frequency range. In many existing modulated current generators, pulse shape stabilization is maintained only in a limited frequency range. Therefore, when analyzing the effect of current modulation frequency on the penetration capacity of the arc in TIG welding, it is necessary to take into account not only the modulation frequency, but also the change in the pulse shape depending on their repetition frequency. Attention to this was first drawn in [6].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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