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Determination of Welding Characteristics of Controlled Metal Transfer in the Arc of Self-Shielded Electrodes

Abstract: Surfacing with self-shielded flux-cored wires, referred to in scientific publications and encountered in industrial practice, is performed using welding equipment of output voltage characteristics. The transfer of metal in the arc is stochastic, usually within a mixed arc, where the short-circuit flow is accompanied by an unfavourable, i.e. globular, one. For this reason, the above-named processes are characterised by significant spatter. The research work presents an original method for shaping the characteristics of pulsed arc, enabling the controlled short-circuit-free transport of droplets. The impulse characteristic differs considerably from that applied previously in the pulsed arc, used to melt solid wires.

Key words: pulsed welding, metal transfer, pulse parameters

DOI: 10.32730/mswt.2024.68.1.3

1. Introduction

During the refurbishment and production of working elements of machinery exposed to rapid abrasive wear, the most frequently used filler metals include core wires, the use of which enables the formation of hard coatings characterised by a high carbon content [1] and martensitic-austenitic structures containing chromium or boron carbides and nitrides. In addition to the chemical composition of the filler metal, the properties of surfaced layers are affected by technological process parameters including welding current, arc voltage and electrode extension [2]. However, little attention is paid to phenomena related to the transfer of metal as it is difficult to properly analyse the dynamic characteristics of arc. This issue is particularly important in cases of flux-cored wires, in relation to which the range of parameters recommended by the manufacturer is often in the area of mixed arc [3, 4], characterised by high instability.

Reference publications present various methods enabling the improvement of properties of melt pool solidifying metal such as the electromagnetic stirring of the melt pool [5], the melting of additional wire in the melt pool [6] and surface solidification [7]. The aforesaid methods also include the obtainment of the uniform transfer of the filler metal [8], which can be achieved by the application of a properly programmed current-voltage waveform of the pulsed arc [9, 10]. The necessity of controlling phenomena taking place during the melting of electrodes during hard surfacing constitutes the primary reason for undertaking the research and analysis presented in the article, aimed at obtaining the fully controlled formation of overlay welds. Previous attempts at implementing parameters describing the characteristics of pulsed arc in self-shielded wires failed to enable the obtainment of the regular transfer of droplets and, because of low process stability, surfacing is characterised by the formation of spatter [11] and failure to obtain satisfactory properties of surface layers [12].

2. Test objective and methodology

The article presents results of experimental tests aimed at determining conditions where the effect of the current-voltage pulse will result in the controlled transfer of metal during hard surfacing performed with a flux-cored wire (i.e. Flux-Cored Arc Welding).

The research work involved the identification of the pulse waveform enabling the formation of drops and their short-circuit-free transfer in the arc. The study also included a detailed analysis of the electrode wire melting rate, used to determine the frequency-rate characteristics as well as to identify the correlation between the filler metal wire

Table 1. Characteristics of the filler metal used in the tests

Wire type	Diameter d_e [mm]	Cross-section	Coat area [mm²]	Chemical composition [%]				
				Coat*	Weld deposit			
				Fe	C	Cr	V	W
MOST F64	1.2		0.7	100	3.8	22	0.8	0.8

*Spectral analysis results (EDS)

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feed rate and pulsing frequency. The determination of the above-named correlation necessitated the assessment of the size of drops separated during the time of the previously programmed current-voltage impulse and the duration of the impulse itself.

The tests involved the use of flux-cored self-shielded filler metal wire F64 (T Fe 16-65 GZ in accordance with PN EN 14700) (MOST) (Table 1).

The tests were performed using two spot-programmable welding machines, i.e. a Quinto 353 Profi welding power source featuring frequency conversion on the secondary side (chopper type) (Cloos) and an AristoMig 4004i Pulse welding power source with frequency conversion on the primary side (from ESAB).

The simultaneous analysis of welding current and arc voltage waveforms in time along with the simultaneous imaging of metal melting processes taking place in the inter-electrode space was performed using a measurement system provided with current and voltage transducers, whose signal was acquired using an NI USB -6251 DAQ device synchronised with a PHOTRON 1024 high-speed digital camera via a MAGMA substation (Mobility Electronics). The small size of the test element necessitated the use of a macro-type lens. In order to obtain the uniform illumination of the area subjected to tests, the light emitted by the discharge lamp was collimated in a Fresnel lens placed between the arc and the light source. The recording speed was 10,000 frames per second.

3. Current-voltage impulse waveform

The research-related tests involved the performance of numerous experiments including the assessment of impulse arc parameters on the formation of the drop and area reduction between the drop and the filler metal wire. Detailed information concerning the methods and test results can be found in publication [13].

The phenomenological analysis revealed that the controlled separation of the drop in the arc of self-shielded electrodes was disturbed by many disadvantageous phenomena accompanying the melting of the filler metal wire, including:

1. High sensitivity of the newly-formed drop to pressure exerted by the magnetic field in the current circuit, manifested by the explosive form of metal transfer.
2. Drop vibrations triggered by metallurgical reactions responsible for the deflection of the drop from the electrode axis, leading to repulsive transfer.
3. Significant scatter of sizes of separated drops was caused by the non-uniform melting of the steel side surface of the filler metal wire, flux and deoxidisers contained therein.

For the above-presented reasons, it is impossible to obtain the classical pulsed process, where the formation and separation of the drop take place during one current-voltage impulse.

The proper course of drop transfer is possible when the current impulse affects the initially formed drop. For this reason, the single welding (surfacing) cycle should consist

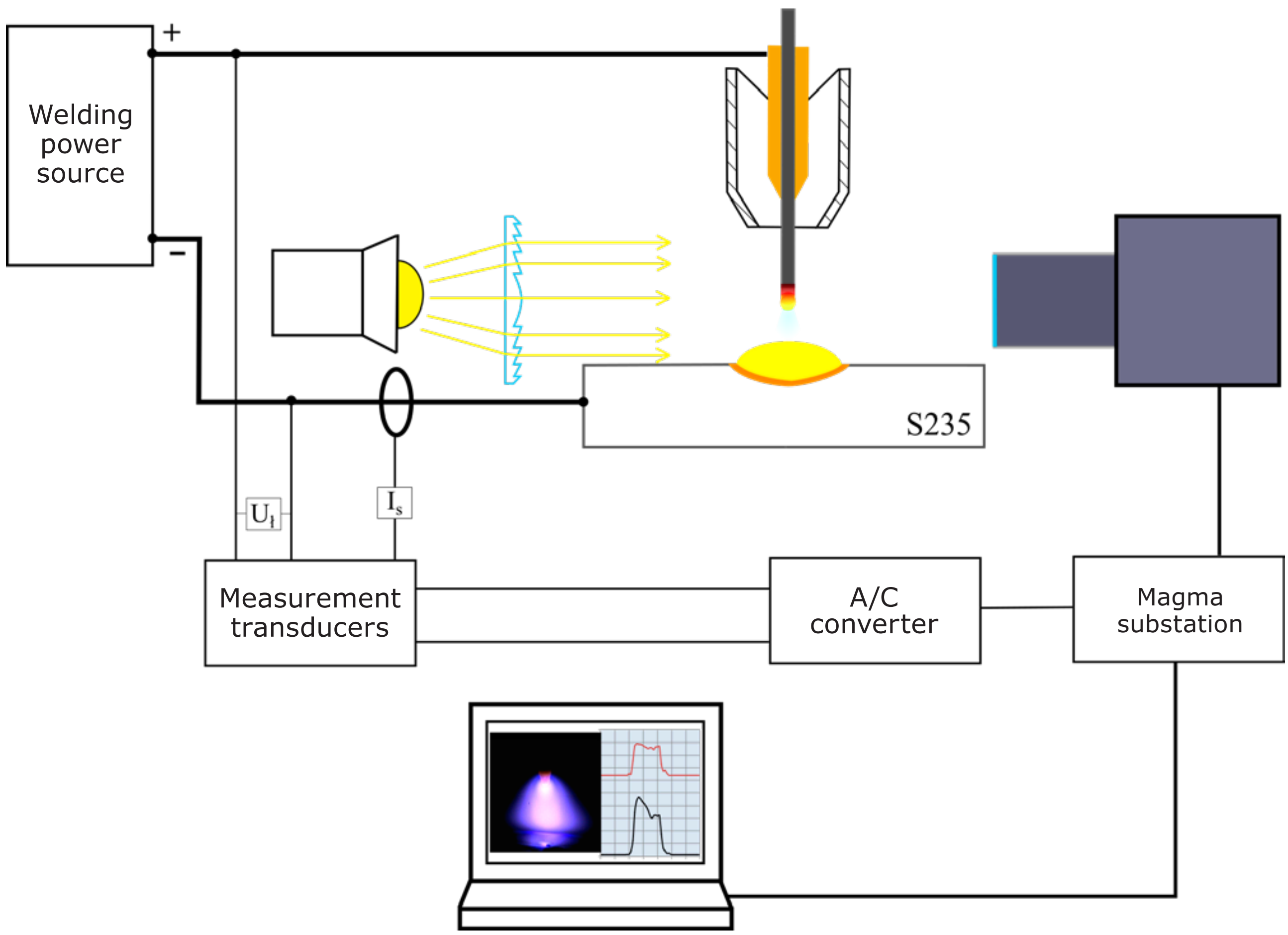


Fig. 1 Schematic diagram of the test rig

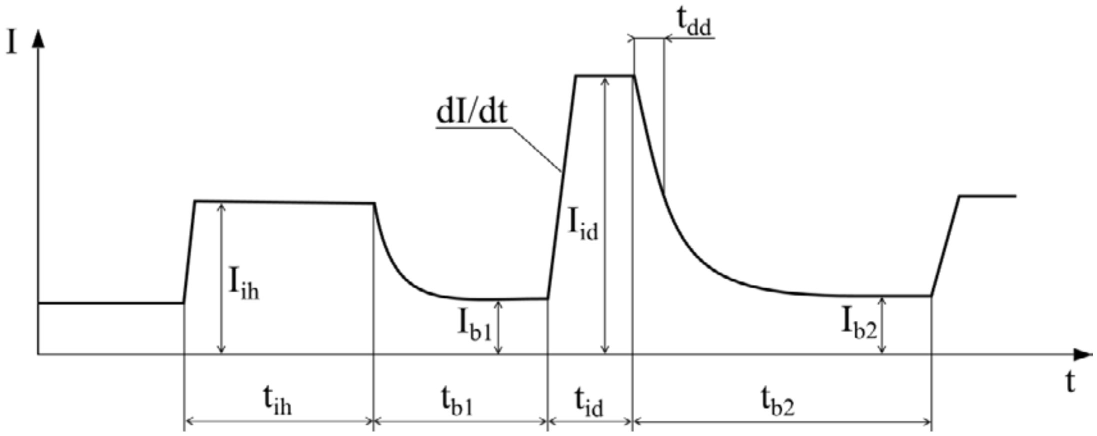


Fig. 2 Proposed current waveform of the double impulse process melting the filler metal wire and separating the drop of liquid metal

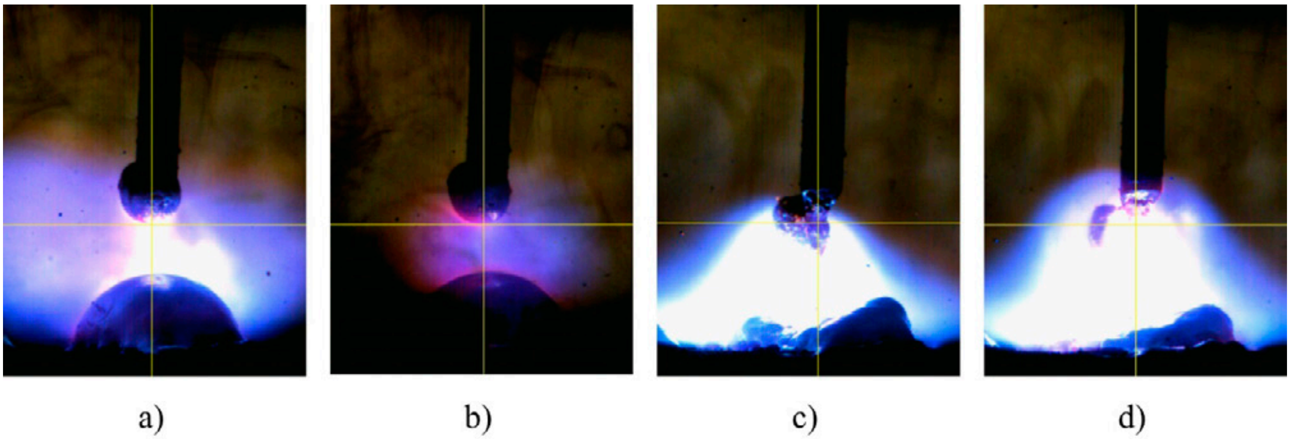


Fig. 3 Transfer of metal in the double-pulse process: a) heating impulse, b) transition phase between working impulse, c) phase of separation impulse current up-slope and the reduction of the area between the drop and the filler metal wire and d) separation of the drop during the final impulse phase

of two coupled current-voltage impulses I_i (Fig. 2), i.e. heating impulse I_{ih} and separating impulse I_{id}. The dynamic characteristic is shaped by nine primary parameters including amplitude of current I_{ih} and the duration of the first part of cycle t_{ih}, current impulse up-slope rate dI/dt, amplitude of current I_{id} and the duration of the second impulse t_{id}, (when the drop is separated), current I_{b1}, duration of transition phase t_{b1} as well as current and duration of basic phase – I_{b2} and t_{b2}.

Figure 3 presents the inter-electrode space during the impulse cycle. The first impulse, referred to as heating impulse I_h, is tasked with melting the specific volume of the filler metal wire (Fig. 3a). Because in this phase of the cycle it is necessary to prevent the separation of the drop, the value of amplitude should not exceed 350 A. At the same time, impulse current I_{ih} should not be overly low as it would require the unnecessary extension of time t_{ih}. Approximately, the value of amplitude I_{ih}, making it possible to control the amount of molten material, is restricted within the range of 150 A to 350 A. By changing the value of amplitude it is possible to control the volume of molten material, which can be used as the process corrector adjusting the length of the arc.

The subsequent part of the cycle is transition phase t_{b1}, where the value of current I_{b1} amounts to 30 A (Fig. 3b). The transition phase, having a duration of 5 ms, prevents the repulsive transfer, which takes place when impulses directly follow one another, i.e. when t_{b1} = 0. The transition phase is also characterised by the stabilisation of the drop (formed by the heating impulse) vibrating at the tip of the filler metal wire. The second impulse, having the higher value of amplitude I_{id}, restricted within the range of 450A to 480 A and characterised by an impulse current up-slope time of 800 A·ms^{-1}, "squeezes" the neck of liquid metal (Fig. 3c) and triggers the separation of the drop. It is essential that the drop should be separated still during the impulse phase (Fig. 3d). During the flow of basic current,

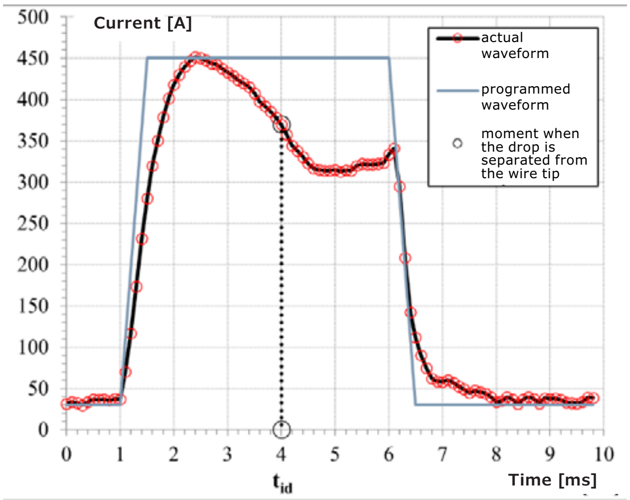


Fig. 4 Actual and declared welding power source impulse current waveforms of voltage output characteristic in the pulsed current phase

an upward longitudinal electrodynamic force prevents the transfer of metal and, if the duration of the impulse is overly short, gravitational force proves insufficient for the separation and transfer of the drop to the melt pool. The test results revealed that the duration (time) of impulse t_{id} should amount to 3 ms.

In addition, the results of experimental tests revealed that the above-presented impulse cycle could be significantly simplified by "shifting" heating impulse I_{ih} until the moment corresponding to the separation of the drop t_{id}. When using a power supply unit with static constant-voltage characteristic in the impulse phase, the appropriate reduction of the value of current directly before the separation of the drop and during the heating impulse (forming the drop) takes place as a result of the feedback of the internal arc–power supply unit system (Fig. 4), consistent with the self-adjustment of the arc in the MAG process [14].

The proper course of the two-stage impulse phase is then only determined by three parameters, i.e. impulse voltage U_i (affecting the value of current amplitude), impulse duration (time) t_i and the current up-slope rate during the impulse phase dI/dt. Because of low current values (which, during the basic phase may amount to less than 10 A) and the limited thermal ionisation of the inter-electrode space in the basic face, in order to prevent arc termination it is usually necessary to apply the exponential transition of current from I_i to I_b. Because the time of drop separation t_{id} (as specified before) amounts to 3 ms, the explicit determination of the value of impulse requires the identification of the average size of the drop separated in the impulse process and, based on this, assess the duration of impulse t_i.

4. Frequency-speed characteristic

4.1. Drop size determination

Using the criterion of the stable course of the gas metal arc welding (surfacing) it was necessary to assume that the average travel rate of the filler metal wire and its melting rate were as follows:

$$\overline{V}_e = \overline{V}_{st} \quad [\mathrm{mm \cdot s^{-1}}] \tag{1}$$

In order to satisfy the above-presented condition, during one impulse cycle, an increase in the electrode (filler metal wire) extension should be melted by the following current impulse:

$$\Delta l_e = V_{st} t_i \quad [\mathrm{mm}] \tag{2}$$

The volume of drop amounted to:

$$v_k = s_0 \, \Delta l_e \quad [\mathrm{mm^3}] \tag{3}$$

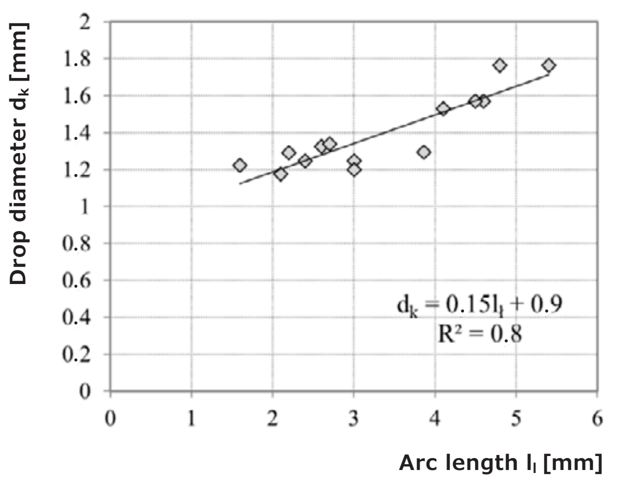
where s_0 – cross-sectional area of the filler metal wire [$\mathrm{mm^2}$]

Therefore, the required impulsing frequency amounted to:

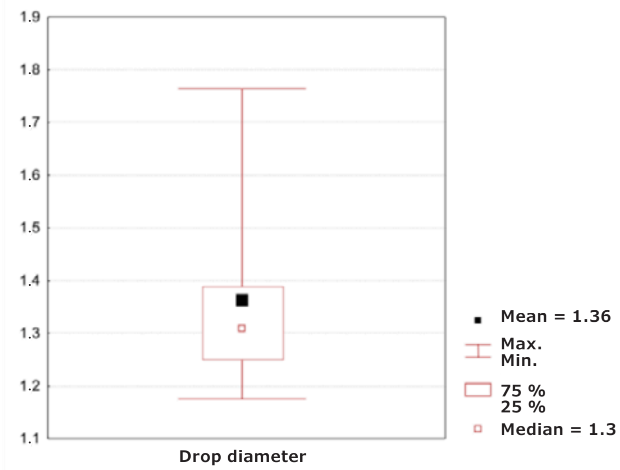
$$f_i = \frac{s_0 v_e}{v_k} \quad [\mathrm{Hz}] \tag{4}$$

Adopting the constant value of current amplitude amounting to 450 A and using the photograph of the inter-electrode space it was possible to identify the average diameter of drops separated from the filler metal wire tip. It was also possible to observe the correlation between the size of separated drops and the length of the welding arc at the initial moment of the impulse (Fig. 5a). In relation to the short arc, the diameter of drops separated from the wire was similar to the wire diameter. Along with the growing distance between the heat source and the electrode, the viscosity of the metal increased and drops separated from the wire tip were characterised by larger diameters.

As the diameter of drops separated from the filler metal wire was restricted within the wide range of 1.15 mm to 1.76 mm, it was necessary to perform statistical analysis aimed at identifying the value (size) which would be the most characteristic of the population subjected to investigation. Figure 5b) contains a diagram presenting the differentiation of drop diameter values. Based on the diagram it was possible to notice the significant similarity of typical units (restricted within the range of the lower and upper quartile). Because the value of the arithmetic mean was located near the upper quartile, the value recognised as representative of drop volume was the median amounting to 1.3 mm and located in the centre of typical units. Based on the aforesaid statistical quantity it was possible to assume that the formation of the drop having a diameter of approximately 1.3 mm would be accompanied by



a)



b)

Fig. 5 Correlation between the drop diameter and the arc length a) and differentiation of diameters of drops separated from the wire b) the process of controlled metal transfer triggered by the forced current-voltage impulse.

4.2. Determination of current impulse duration

To ensure process stability, in accordance with equation (3), impulse current should melt the volume of the electrode equal to:

$$\frac{1}{6}\pi\, d_k^{\,3} = s_0\,\Delta l_e \quad [\text{mm}^3] \tag{5}$$

The filler metal wire melting rate depended on the heat of the arc and the resistance heating of the active part of the electrode. The thermal balance of the melting of a given drop volume within one impulse cycle is expressed by the following equation:

$$H_m\, m_k = q_a\, t_i + R_e\, I_i^2 t_i + q_a\, I_b\, t_b + R_e\, I_b^2 t_b - \theta \quad [\text{J}] \tag{6}$$

where

H_m – amount of energy needed to melt one gram of steel was 1440 Jg^{-1}, according to Halmoy [15] and 1308 $J{\cdot}g^{-1}$, according to Tichelaar et al [16]

q_a – metal heating rate by arc heat [W]

R_e – resistance of electrode (filler metal wire) extension

θ – heat losses, usually negligible in analysis [15, 17, and 18]

The heating of the electrode by the arc in the impulse phase is expressed in detail by the following dependence:

$$Q_a = \left(V_a + \phi + \frac{3kT}{2e}\right)\cdot \int I(t)\,dt \quad [\text{J}] \tag{7}$$

where

V_a – in relation to consumable electrodes, the value of anode drop was restricted within the range of 1.5 V to 2 V

ϕ – in relation to steel, electronic work function dependent on the state of the liquid metal surface and the temperature of the drop was restricted within the range of 3.5 V to 4.5 V Lancaster [17]

k – Boltzmann constant [$J{\cdot}K^{-1}$]

T – temperature of electron moving in plasma [K]

e – electric charge of electron [C]

Based on experimental data it could be assumed that $V_a + \phi + \frac{3kT}{2e} = 6\text{V}$ [19, 20]. However, according to the most recent tests this value is considered to stand at 7 V [21]. The equation of heat emitted during the flow of basic current is determined in the analogical way.

The thermal balance of filler metal wire heating is connected with many forms of heat transfer. Because the Prandtl number for steels and most liquid metals $Pr < 0.1$, therefore, when considering arc heat diffusion, conduction is of primary importance. In the GMAW process, the transfer of heat inside the drop is also triggered by thermocapillary phenomena (gradient of surface tension) and the movement of liquid triggered by electromagnetic forces [19]. Because of the lack of appropriate boundary conditions and the poorly determinable actual shape of the molten part of the electrode, it was impossible to perform numerical calculations [22]. For this reason, when analysing phenomena connected with the transfer of heat, the Author performed an experiment where the arc was burning on the surface of the filler metal wire which was in the stationary (fixed) position, where $V_e = 0$ $m{\cdot}min^{-1}$. In this way, when the Péclet number was equal to zero, the observation of a linear increase in the volume of molten metal enabled the identification of melting rate changes in time, dependent on the momentary value of current and the state of the electrode. The conclusions of the observations are presented below (Fig. 6):

The highest electrode melting rate was observed during t_{id}–t_{ik}, (heating phase t_h), after the separation of the drop from the filler metal wire tip, which was connected with the condensation of electrons on the side surface of the filler metal wire [23]. Such an increase in the welding rate was also probably induced by the greater value of near-electrode voltage drop and, at the same time, by an increase in power in the anode area [17].

4. At the initial phase of impulse t_{i0}–t_{i1}, the heat of the arc was absorbed on the surface of the drop and transported along the electrode axis, thus triggering an increase in the temperature of the filler metal wire and its melting. The melting rate was lower than that in phase t_h, by, on average, 0.24 $m{\cdot}s^{-1}$. Similar welding rates were observed during impulse down-slope time (t_{ik}–t_c).
5. Time interval t_{i1}–t_{id} was the phase of an increase in drop temperature as no significant increase in molten volume was observed. Such a situation was connected with a decrease in the cross-section through which heat was conducted from the (heated) drop to the filler metal wire (reduction of cross-sectional area and the separation of the drop). As a result, arc heat would increase the temperature of the drop above the melting point of the metal depending on the momentary value of current and the time of drop separation from the tip of the filler metal wire.

Based on the analysis it was assumed that the melting of the electrode took place:

1. after the separation of the drop during t_{id}–t_{ik} and t_{ik}–t_c (Fig. 6),
2. at the initial phase of the separating impulse, until the formation of area reduction t_{i0}–t_{i1}.

In order to facilitate the perception of the previously adopted assumptions, the Authors presented the detailed course of calculations used to determine the required time of impulse (Table 2). Because the time of drop separation (time of separating impulse t_{i0}–t_{id}) amounted to 3 ms, the value to be identified was time t_{id}–t_{ik}.

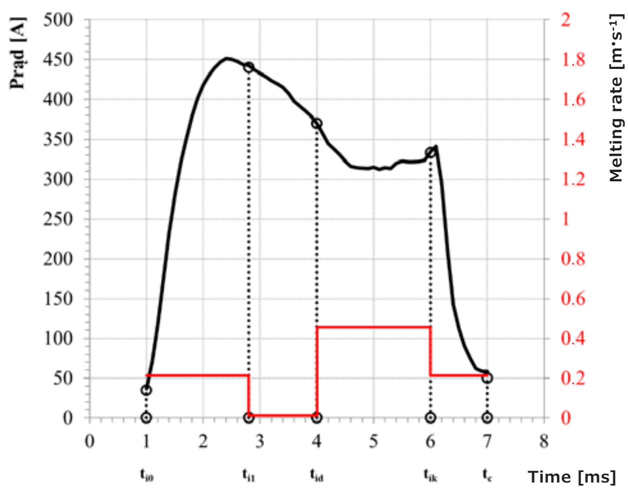


Fig. 6. Average melting rates dependent on the physical state of the filler metal wire tip during the time of current impulse

Table 2. Course of analytical calculations of impulse duration

Input data	Course of calculations	Results
	1. It was assumed that heat melted the electrode during time t_{i0}-t_{i1} and t_{id}-t_c (Fig. 6). 2. Based on the dynamic characteristic it was possible to determine the heat of impulse arc in time t_{i0}-t_{i1} and t_{ik}-t_c.	
$V_a + \phi + \frac{3kT}{2e} = 6$ [V]	$Q_{at_{i0}-t_{i1}} = \left(V_a + \phi + \frac{3kT}{2e}\right) \cdot \int I(t)dt$ $Q_{at_{i0}-t_{i1}} = 3.5$ [J] $Q_{at_{ik}-t_{ic}} = \left(V_a + \phi + \frac{3kT}{2e}\right) \cdot \int I(t)dt$ $Q_{at_{ik}-t_{ic}} = 0.4$ [J]	$Q_{at_{i0}-t_{i1}} = 4$ [J] $Q_{at_{ik}-t_{ic}} = 0.4$ [J]
	3. Determination of electrode extension resistance	
$\bar{\rho} = 0{,}495$ [mΩ·mm] $l_e = 10$ [mm] $s_0 = 0{,}7$[mm^2]	$R_e = \bar{\rho}\frac{l_e}{s_0}$ $R_e = 0.495\frac{10}{0.7}$ $R_e = 7$ [mΩ] NOTE: Value was the resistivity of the electrode extension during welding, adopted on the basis of infrared test results.	$R_e = 7$ [mΩ]
	4. Calculation of current flow-triggered heat emitted in the electrode extension	
$R_e = 7$ [mΩ]	$Q_{et_{i0}-t_{id}} = R_e\int I(t)dt$ $Q_{et_{i0}-t_{id}} = 3.5$ [J] $Q_{et_{ik}-t_{ic}} = R_e\int I(t)dt$ $Q_{et_{ik}-t_{ic}} = 0.4$ [J]	$Q_{et_{i0}-t_{id}} = 3.5$ [J] $Q_{et_{ik}-t_{ic}} = 0.4$ [J]
	5. Calculation of heat H necessary for melting the electrode within one impulse cycle	
$v_e = 1{,}14$ [mm^3] $\rho_s = 7{,}8\cdot10^{-3}$ [g/mm^3] $H_m = 1440$ [J/g]	$H = H_m v_e \rho_s = 12.8$ [J]	$H = 12.8$ [J]
	6. It was ascertained that the transfer of the drop was stable when the value of current in time t_{id}-t_{ik} was restricted within the range of 300 A to 330 A. The use of the average value of current amounting to 315 A in equation (6) enabled the obtainment of required impulse time t_{id}-t_{ik}. The total impulse time amounted to 5 ms.	$t_{id} - t_{ik} = 2$ [ms]

5. Conclusions

1. The proper course of the melting process and the short-circuit-free transfer of the drop in the self-shielded electrode arc was possible due to the two-stage waveform of the current impulse.
2. The coupling of the external voltage static characteristic (constant-voltage one in the impulse phase) of the power supply unit and the arc welding characteristic ensured the controlled transfer of metal and enabled the reduction of descriptive process parameters in relation to the multipulse waveform.
3. Based on the phenomenology of the inter-electrode space it was found that the filler metal wire (electrode wire) melting rate depended on the transfer of arc heat deep inside the filler metal wire and changed during the impulse phase.
4. The tests revealed that the duration of the separating impulse should amount to 3 ms, whereas the estimated duration of the impulse preparing the drop amounted to 2 ms. The above-presented impulse duration enabled the stable transfer of metal in the arc, whereas the heat input in the impulse phase melted the drop having a previously assumed diameter of 1.3 mm.
5. The above-presented methods and results could be useful when determining pulse surfacing characteristics for other types of electrodes.

Acknowledgements

The Authors wish to express their thanks to employees of the ESAB company for providing welding equipment used in the tests presented in the article.

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