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The Influence of Pulse Current Frequency on Selected Aspects of Heat Transfer during GTA Welding of 321 Steel

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Abstract: Heat input is one of the parameters describing the arc welding process shown in the welding procedure specification. However, there is a strong need to precise its determination particularly when welding with arc pulsation. The paper presents an experiment illustrating the influence of the pulsed current frequency on heat transfer results when welding 321 steel with the GTAW method.

Introduction

The significance of knowledge about heat input in arc welding is well understood. But the issue of heat input representing the energy delivered to the workpiece in relation to the unit length causes many controversies. In recent years, several studies have been developed to underline the strong need to precise this technological parameter, which is widely used in industry and mentioned in the welding procedure specification (WPS). Welding standards, recommendations, and procedures usually determine ranges that the predicted heat input must fall within. But there are differences in the recommendations and formulas for heat input calculations depending on the country. Besides, the ranges of recommended heat input are sometimes very wide. The measurement and calculation aspect in relation to pulsed current processes [1, 2] is particularly controversial. Some welding equipment companies offer devices for measuring the heat input of pulsed current welding process in accordance with the newest interpretation of US standards. Unfortunately, the usage of these devices on the Polish market is still rare. In the case of pulsed current GTA welding at various pulsation frequencies, different results can be obtained for the same calculated value of heat input. These differences arise regardless of the calculation or measurement methodology used. Therefore, one can ask the question about the usefulness of a process parameter which at constant value cannot guarantee the same welding result.

Experimental procedure

In order to determinate the influence of the pulse current frequency on heat transfer during GTAW welding, the following experiment was performed:

1. mechanized pulsed current tungsten arc welding,
2. oscilloscope measurements of welding current and arc voltage and calculation of the heat input value,
3. macro- and microscopic observations of the structures of welds.

Workpieces of 321 steel [3] with dimensions of 250 x 50 x 3 mm were fixed on a copper back plate. Due to the possibility of precise setting of welding current pulsation parameters, Fronius TIG MagicWave 2500 DC power was used. The torch with the 2.4 mm 1.5% lanthanated tungsten electrode was mounted on the line positioner. The process was performed with no filler material. As a shielding gas pure argon (9.8 l/min. flow) was used.

The measurements were performed with the Siglent SDS 1072CML oscilloscope and an intermediary KWR1 casette containing the necessary current and voltage measuring transducers [4]. The oscilloscope has two independent measuring channels with a range of 70 MHz. The screen displayed voltage and current waveforms as a function of time and measured true RMS and average values for these parameters.

Table 1 Scheduled process parameters

Waveform color	Pulse current I_p	Base current I_b	Average current I_{av}	RMS current I_{RMS}	Duty cycle ratio r_i	Current ratio r_e	Welding speed v [mm/s]
blue	150	20	85	107	0.5	0.13	2.33
red	130	40	85	96	0.5	0.31	2.33
green	110	60	85	88.6	0.5	0.55	2.33

The current and voltage measurements were made at the process stabilization and included an average calculated from a minimum of 5 pulse cycles. For microstructure observation Olympus BX 51M microscope was used. The etching was performed with the Mi16Fe reagent. Standard metallographic procedures were adopted for examining the microstructure of the weldments. The experiment included the execution of the waveforms shown in Fig.1 for three pulsation frequencies: 5.20 and 100 Hz. Settings on the device and calculated values of average and RMS current at 50% pulse duty ratio are given in Table 1.

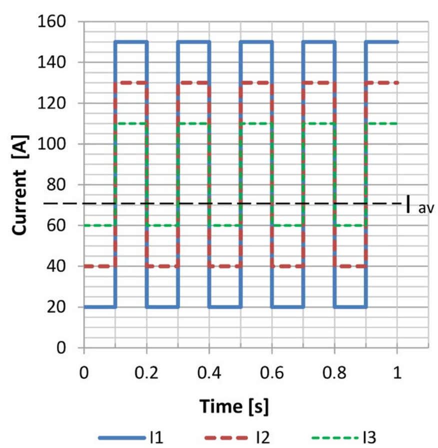

Fig. 1 The waveforms representing the settings on the device for f = 5 Hz

Considering the rectangular waveform, it is possible to analyze the electrical aspect of the arc's operation in terms of average or RMS current values. The average pulse intensity can be calculated using the following formula (1):

$$I_{av} = \frac{1}{T}\int_0^T I\,dt = \frac{(I_p \cdot t_p) + (I_b \cdot t_b)}{(t_p + t_b)} \tag{1}$$

where: $T = t_p + t_b$ (period); t_p - duration of the pulse; t_b- duration of the base current; I_p and I_b - the current of the pulse and the base current, respectively

When calculating the RMS current value, the following formula should be used (2):

$$I_{RMS} = \frac{1}{T}\left[\int_0^T I^2\,dt\right]^{\frac{1}{2}} = \left[\frac{\left(I_p{}^2 \cdot t_p\right) + \left(I_b{}^2 \cdot t_b\right)}{\left(t_p + t_b\right)}\right]^{\frac{1}{2}} \quad (2)$$

r_e, r_i are defined:

$$r_e = \frac{I_b}{I_p}$$

current ratio

$$r_i = \frac{t_p}{T}$$

duty cycle ratio

The relation between the average and RMS current value of the current is as follows(3) [5]:

$$\frac{I_{av}}{I_{RMS}} = \frac{r_i + r_e \cdot (1 - r_i)}{(r_i + r_e^2 \cdot (1 - r_i))^{\frac{1}{2}}} \quad (3)$$

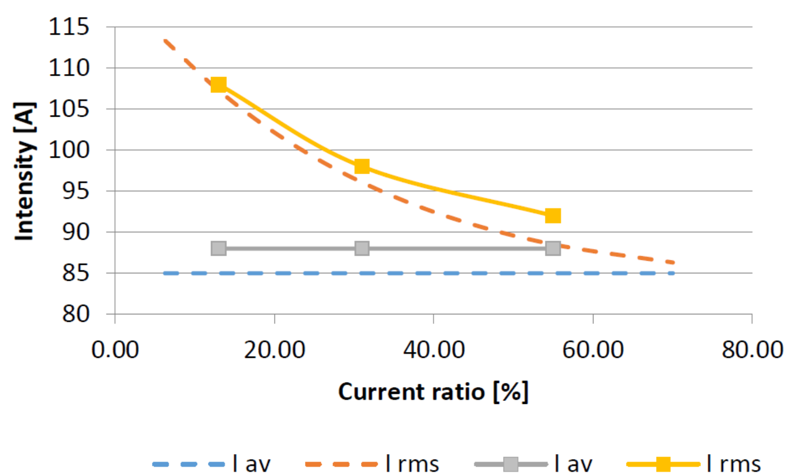

Fig. 2 Current intensity and current ratio dependence:
full lines – experimental results; dashed lines – calculations from formulas (1.2).

The above dependence indicates that the average current intensity is lower than the RMS one and the difference between I_{RMS} and I_{av} is the higher the lower the r_e and r_i values are, which is confirmed both at the theoretical level (TABLE 1) and during measurements and calculations made as part of this work (TABLE 2, Fig. 2). This leads to the conclusion that the use of average values in the calculation of pulse waveforms will cause large deviations from the real values, and for heat input it could be up to 30 % [2].

Results and discussion

It was observed that according to the change in the current ratio there is a slight change in voltage for both average and RMS values (Table 2). The average intensity is constant in all cases, whereas the RMS one decreases with the increase of the current ratio.

TABLE 2. Actual parameter values measured using an oscilloscope and HI calculation

Spec.	Settings		Measurements				Calculations	
	Pulse/base current	f [Hz]	I_{av} [A]	I_{RMS} [A]	U_{av} [V]	U_{RMS} [V]	HI_{av} [kJ/mm]	HI_{RMS} [kJ/mm]
1	150/20	5	88	108	14.4	15.2	0.33	0.42
2	150/20	20	88	108	14.4	15.2	0.33	0.42
3	150/20	100	88	108	14.4	15.2	0.33	0.42
4	130/40	5	88	98	12.8	13.6	0.29	0.34
5	130/40	20	90	98	12.8	14.4	0.30	0.36
6	130/40	100	90	100	12.8	13.6	0.30	0.35
7	110/60	5	88	92	12.8	14.4	0.29	0.34
8	110/60	20	88	92	12.8	14.4	0.29	0.34
9	110/60	100	90	94	13.6	14.4	0.32	0.35

The frequency of current pulsation has no influence on the voltage and current in the given range of parameters. Instantaneous voltage changes can be interpreted by the weld pool oscillation during operation of the heat source, which leads to short-term changes in the arc length [5, 6]. Measured values were used to calculate heat input based on the following dependence (4) [7]:

$$HI = k \cdot \frac{U \cdot I}{v} \cdot 10^{-3} \tag{4}$$

where: HI – [kJ/mm], k - arc efficiency, U - arc voltage, I - welding current, v - welding speed

According to the conventional approach, arc efficiency coefficient k = 0.6 was assumed. Heat input values were calculated based on average and RMS values of voltage and current and the results were presented in TABLE 2.

The highest values of heat input (both for average and RMS parameters) were obtained for the process at the current ratio of 0.13 (samples 1 to 3 in Table 3). In the case of processes performed at 0.31 and 0.55 current ratios, the heat input values were similar. Heat input values calculated on the basis of RMS values were higher than those calculated from average ones and decreased according to the increase of the current ratio. In the formula (4), the pulsation frequency is not considered. Therefore, it would be necessary to exclude its influence on the calculated heat input of the process.

In macrostructure of the obtained weldments no physical surface defects like arc strike, cracks, and undercut were observed. Changes in the cross-sectional area of fusion zone can be considered as small (TABLE 3). However, comparison of the cross-sectional areas of the welds can provide information on the differences in the thermal efficiency. This information is of a general nature and its value is limited to a relative term, in which case the volume of molten material represented by the cross-section of the weld is greater than that of the other samples. The relationship between the amount of heat input and weld cross-section area is currently the subject of investigators' interest [8, 9] but it is an important part of the analysis of the heat input as a process parameter.

The quantitative aspect of the dependence between the melted area and the heat input can be described by formula (5) [10]:

$$A = \frac{k' \cdot k \cdot I \cdot U}{H \cdot v} \tag{5}$$

where: A - cross-sectional area [mm^3], k' and k melting and arc efficiency, respectively, I - welding current intensity [A], U - arc voltage [V], v - welding speed [mm/s] H - the theoretical amount of heat necessary to melt the volume unit of metal J/mm^3 (melting enthalpy).

The highest cross-sectional value (9 mm^2) was obtained for specimen 3 welded with the process parameters: I_p = 150A, I_b = 20 A and f = 100 Hz. The lowest cross-sectional area (4.95 mm^2) was obtained for sample 9 with the parameters: I_p = 110 A, I_b = 60 A and f = 100 Hz. With reference to formula (5), the conclusion arises that the change in the pulsation frequency affects the melting efficiency and/or thermal efficiency. The volume of molten metal for the current ratio of 0.13 increases with increasing frequency. It should be noted that for different current ratio, the frequency of pulsations exhibits different tendencies of such changes (Fig. 3, Fig. 4)

TABLE 3. Weld cross-section areas in dependence on process parameters

Spec.	1	2	3	4	5	6	7	8	9
Pulse/base current; frequency	150/20A 5 Hz	150/20A 20 Hz	130/40A 100 Hz	130/40A 5 Hz	130/40A 20 Hz	110/60A 100 Hz	110/60A 5 Hz	110/60A 20 Hz	110/60A 100 Hz
A [mm^2]	7.36	8.47	9.0	6.44	5.82	7.24	6.39	6.75	4.95

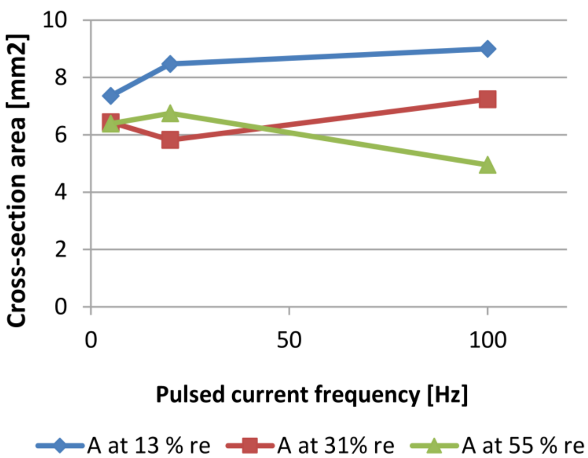

Fig. 3 Cross-sectional area and pulsation frequency dependence at various current ratios

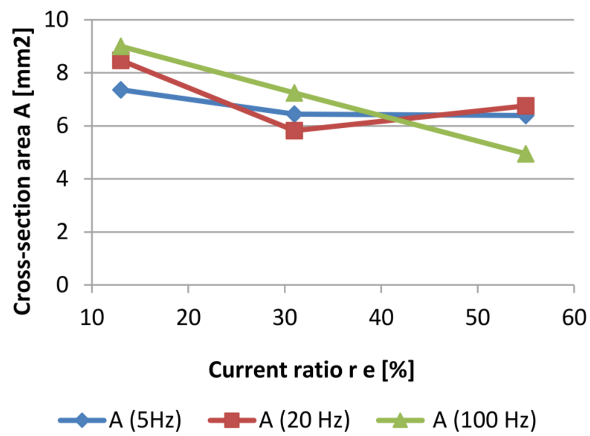

Fig. 4 Cross-sectional area and current ratio dependence at various pulsation frequencies

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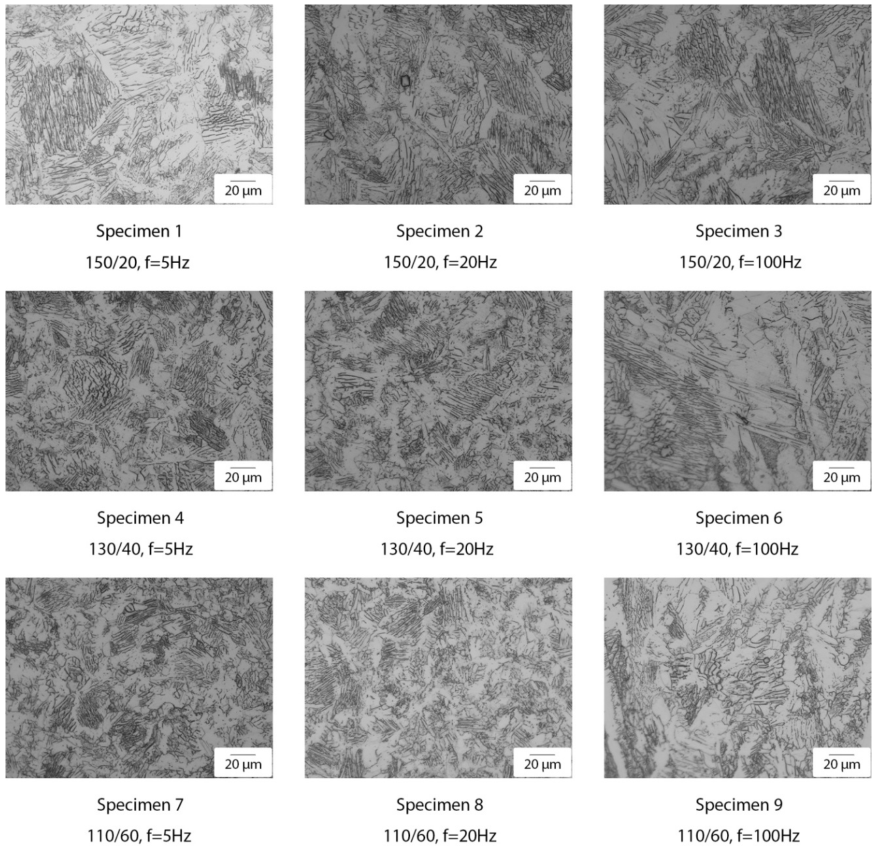

Fig. 5 Microstructures of weld metal at x500 magnification

Weld metal microstructures contained austenitic matrix with delta ferrite in the form of elongated grids and plates (Fig. 5). In the structure of the fusion, heat affected zones and base metal, titanium carbide crystals were present. Closer to the weld face, in the axis of fusion zone, heterogeneous solidification of austenite dendrites could be observed, which may indicate relatively high degree of constitutional supercooling. Delta ferrite was also observed in the HAZ in the form of long stringers arranged according to the direction of steel rolling. The presence of delta ferrite in the structure of such steel is usually explained by the low stability of the austenitic structure. The comparison of microstructures obtained at different current ratios does not provide definitive conclusions, although it may seem that with the increase of the current ratio, the structure became more fine-grained. On the other hand, according to the frequency increase, the structure undergoes a significant change as the austenite grains grow. Such a change must be connected with the extension of the cooling time, and thus the reduction of the cooling rate. The observation of the microstructure led to the conclusion that there are some differences in heat transport in dependence of pulsation frequency. The highest heat input was transferred into the material when melting the sample No. 3 at the settings I_p = 150 A, I_b = 20 A f = 100 Hz. The influence of frequency on the microstructure is visible in all three current ratio settings. Heat input calculations based on formula (4) show no value differences in relation to the pulsation frequency, and therefore are not consistent with the observations of real macro- and microstructures. The results of macroscopic and microscopic investigations lead to the conclusion that they represent different aspects of heat transport to the material. Similar volumes of molten metal can differ significantly in microstructure.

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Conclusions

The frequency of current pulsation does not affect significantly the intensity or arc voltage in the tested frequency range.

1. The calculated heat input values are constant regardless of changes of pulsing frequency. It results from the omitting the effect of the pulsation frequency in the commonly used formula. In fact, the change in the pulsation frequency causes the formation of welds with different cross-sectional area and with different microstructure. The volume of molten metal and microstructure inform about different aspects of heat transport.
2. An increase in the frequency of current pulsation does not necessarily lead to an increase in the depth of penetration.
3. The suitability of the formula for heat input in the context of pulsed TIG welding should be reviewed.

References

[1] P. Cegielski, A. Kolasa, M. Kuczyński, R. Rostkowska, Some aspects of monitoring and measurements during arc welding, Welding Technology Rev. 88 (12) (2016) 43-50. https://doi.org/10.26628/ps.v88i12.719

[2] LEB2/2010 Lincoln Electric

[3] Welding Handbook vol.4. Materials and applications - Part 2.1998. Chapter 5 pp. 233-332

[4] P. Cegielski, Ł. Bugyi, Selected aspects of welding defects identification in MIG/MAG arc welding, Welding Technology Rev. 89 (6) (2017) 30-35. https://doi.org/10.26628/ps.v89i6.784

[5] W. H. Kim, S. J. Na, Heat and fluid flow in pulsed current GTA weld pool, Int. J. Heat Transf. 41 (1998) 3213-3227. https://doi.org/10.1016/S0017-9310(98)00052-0

[6] H. G. Fan, S-J. Na and Y. W. Shiz, Mathematical model of arc in pulsed current gas tungsten arc welding, J. Phys. D: Appl. Phys. 30 (1997) 94–102. https://doi.org/10.1088/0022-3727/30/1/012

[7] PN-EN 1011-1: 2009 Spawanie – Zalecenia dotyczące spawania metali – Część 1: Ogólne wytyczne dotyczące spawania łukowego.

[8] K. Wojsyk, M. Macherzyński, Determination of Welding Linear Energy by Measuring Cross-Sectional Areas of Welds, Biul. Inst. Spaw. 60 (5) (2016) 83-89. https://doi.org/10.17729/ebis.2016.5/11

[9] K. Wojsyk, M. Macherzyński, R. Lis, Evaluation of the amount of heat introduced into the welds and padding welds by means of their transverse fields measurement in conventional and hybrid welding processes, Welding Technology Rev.89 (10) (2017) 67-82.

[10] A. Klimpel, Technologia spawania i cięcia metali, Gliwice, Politechnika Śląska, 1997.