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PC-GMAW EFFECT ON THE WELDING THERMAL CYCLE AND WELD METAL GEOMETRY FOR HIGH STRENGTH STEELS

Abstract. Welding of medium carbon alloy steels used in the manufacture of special-purpose machinery imposes to solve two mutually exclusive problems – to increase the depth of penetration of the base metal and to reduce the width of the thermal impact zone of the welded joints. To successfully solve this problem, it is necessary to use arc welding processes with a concentrated heat source. One of these processes is pulsed current gas metal arc welding (PC-GMAW). The present researches have allowed establishing, that with PC-GMAW change of welding current is a difficult character, namely: on high-frequency impulse signal (60 kHz), impulses of the current of low frequency (from 90–150 Hz) are imposed. The change in the values of the mean welding current at PC-GMAW is achieved by increasing the pause current and the frequency of high-amplitude current pulses. It is shown that the PCGMAW allows reducing the amount of metal splashing, to increase the depth of penetration (almost 2 times) in comparison with stationary welding. At the same time, the cooling rate of HAZ metal in the temperature range 600–500°C decreases almost 1.5 times, which allowed to reduce the width of HAZ by 40%.

Keywords: pulse current gas metal arc welding, welding thermal cycle, heat affected zone, high alloy welding materials.

Abbreviations

HSLA – high-strength low alloyed
TMCP – thermo-mechanical control process
PC-GMAW – pulsed current gas metal arc welding
CE – carbon equivalent
HV – Vickers hardness
HAZ – heat affected zone
Ra – Yield stress
WTC – welding thermal cycles

Introduction

For the production of special-purpose machines, the quenched high-strength alloyed steels are used. While for the manufacture of modern construction and engineering metal structures are needed the high-strength low-alloy steels of strength 460 MPa obtained with thermo-mechanically controlled process (TMCP). At present, to provide the welded joints of these steels with the required complex of mechanical properties their welding is performed in limited modes, which, first of all, makes the welding process inefficient, and, secondly, increases the risk of the formation of unacceptable defects in such compounds such as cold cracks. Usually, in traditional arc welding processes, these issues are solved by increasing welding modes (welding power). However, for modern structural steels, this approach is ineffective, since, with increasing welding conditions in the heat-affected zone (HAZ) of welded joints, there is a decrease of the hardness, strength, and toughness of the metal to a level below the standards. It also increases the size of the HAZ, which adversely affects the durability of welded joints of high-strength steels. It is possible to solve these problems by the partial introduction of heat into the welded joint, which can be realized during pulsed arc welding.

The process of pulsed arc welding differs qualitatively from traditional welding in shielding gases, as well as from manual arc welding with modulated current [1–5]. It is increasingly used in the manufacture of welded structures of aluminium alloys, titanium and structural steels with a strength of up to 500 MPa. This is explained by the fact that the pulse-arc welding expands the control of the processes of melting and transfer of the electrode metal [6–8] in different spatial positions, improves the formation of seams, reduces the mixing of the electrode metal with the base metal and the size of the HAZ [9–15]. This is because such well-known companies Fronius (Austria), Bohler (Germany), ESAB (Sweden) and others pay considerable attention in their activities to the development and production of equipment for the implementation and expansion of the capabilities of the pulse-arc welding process in shielded gas. Much weaker in the technical literature are highlighted the questions about the influence of the parameters of the pulsed arc welding on the thermal processes occurring in the HAZ metal of welded joints, and how they affect the structure and mechanical properties of the metal, its resistance to the formation of cold fractures and cracks etc. It is the uncertainty of these issues that impedes the use of arc welding in shielding gases in the manufacture of metal structures made of steels that are sensitive to thermal processes and prone to hardening.

Methodology

To solve this problem, we performed surfacing of the high-alloy welding wire 1.2 mm diameter HORDA307Ti (EN 14171: G 18 8 Mn Ti), with following chemical composition 0.10 C, 0.8 Si, 6.0 Mn, 20.0Cr, 9.5 Ni, 0.6 Ti wt%. The surfacing was carried out on 10 mm thick plates made of 09G2C steel. Surfaces were made from the surfacing plates, which measured the parameters of the seams and the HAZ. To detect HAZ, the metallographic samples were macro etched with chlorine iron. Recording of the welding thermal cycles (WTC) of the HAZ overheating section was performed using a 0.5 mm Type K thermocouple. The thermocouple was installed on the HAZ section, which was heated to a temperature of 1200°C. The following modes were selected to evaluate the effect of pulsed arc welding modes on the weld parameters: I = 120, 160, 200, 240 A, U = 20, 24, 28, 30 V = 15 m/h, shield gas Ar + 18% CO_2. The ewm Phoenix Pulse 501 inverter type current source, providing different pulse frequency for pulsed arc welding was used. To determine the welding and technological characteristics of the current source, a UTD2000CEX-II digital oscilloscope was used, which allows the voltammeter fixation over a wide range. To record oscillograms used 75SHSM shunt, which has a resistance of 150 μΩ. This allows register welding currents up to 500 A, with the voltage drop across the shunt being 75 mV, respectively. The geometric parameters of the seams were determined by digitizing and using special AxioVision 4.6 software.

Results and discussion

The ewm Phoenix Pulse 501 is an inverter type, and therefore has been compared volt-ampere to a VDU power source equipped with a diode rectifier. From the results shown in Fig. 1, it is evident that these current sources differ significantly in the characteristics of changes in the welding current when operating in a stationary mode.

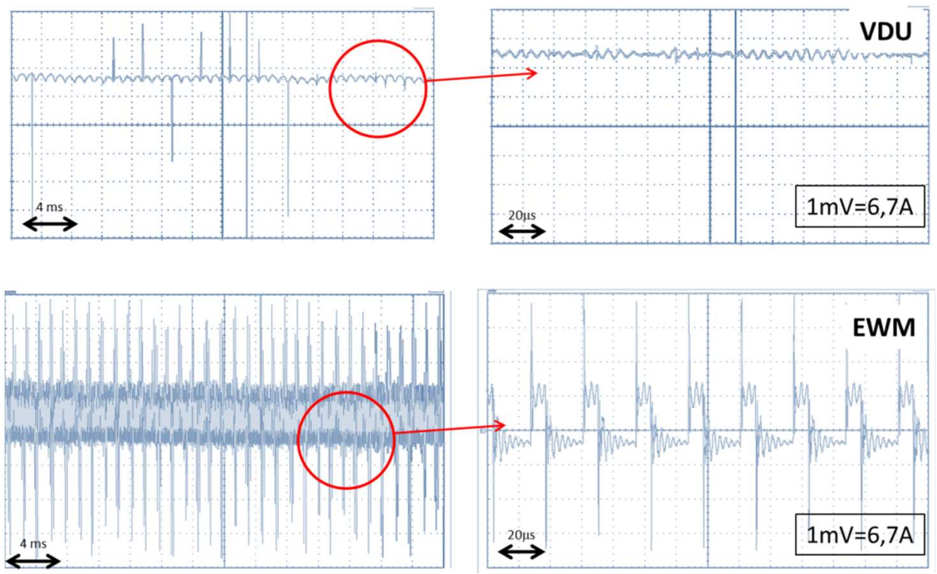

Fig. 1. Welding current waveforms for (a) transformer and (b) inverter types of power supplies (schematic view)

It is established that the steady state welding mode of the VDU power supply is characterized by a direct current with small oscillations (Fig. 1). The value of the current on the waveform corresponds to 120 A. For an ewm Phoenix Pulse 501 power source equipped with an inverter rectifier, the dependence of the welding current change is fundamentally different (Fig. 1). With a small sweep of the waveform (t~ms), a wide band of dense pulses of sufficiently large amplitude is observed (Fig. 1). In order to identify the features of the ampere characteristic, the scale of scanning the oscilloscope to microseconds was enlarged (Fig. 1). Under such conditions, the peculiarities of the change in the welding current, which are of impulse character, appear. The areas of pulse and pause are clearly observed, and oscillating damping oscillations occur at transitions. To calculate the magnitude of the current, the average value of these oscillations was chosen. The pulse repetition rate is 58 kHz and does not change with the increasing welding current. Instead, the duty cycle and current of the pulse are changing Fig. 2.

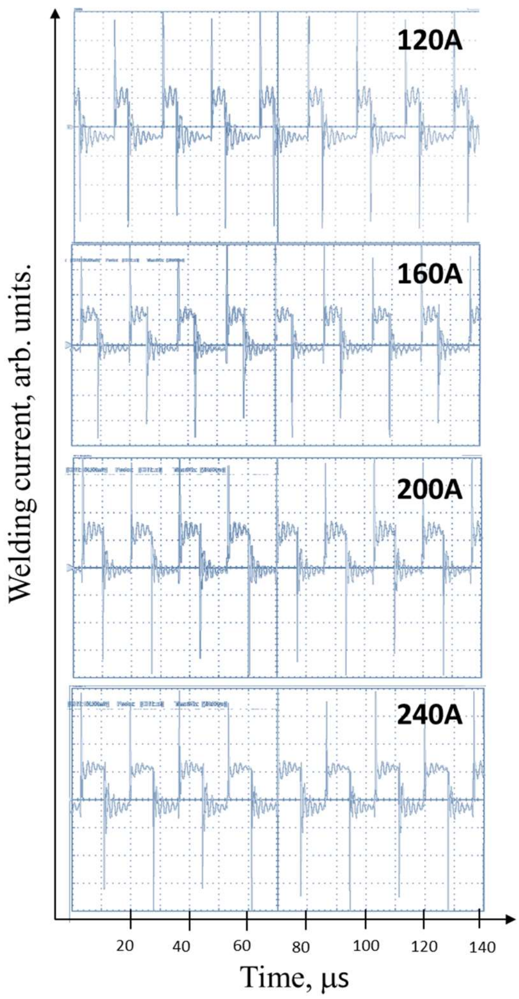

Fig. 2. Waveforms for inverter power supply, stationary welding mode

Analysis of the waveforms for the welding currents under study showed that the pause current was in all cases about zero. For welding current 120 A, which is displayed on the dashboard of the power source, the pulse current is 333 A, its duration t = 2 μs. According to the formula for determining the average welding current

$$I_{av} = \frac{I_{pulse} t_{pulse} + I_{pause} t_{pause}}{t_{pulse} + t_{pause}} \qquad (1)$$

where I_{av} – average current, I_{pulse} – pulse current, I_{pause} – pause current, t_{pulse} – time of pulse, t_{pause} – time of pause, I_{av} = 110 A, that is, 8.3% lower than on the device. The duty cycle (t_{pulse}/T) is 0.33. As the welding current (which is displayed on the instrument) increases, the current in the pulse and the pulse duration at a constant frequency of succession increase (Fig. 3).

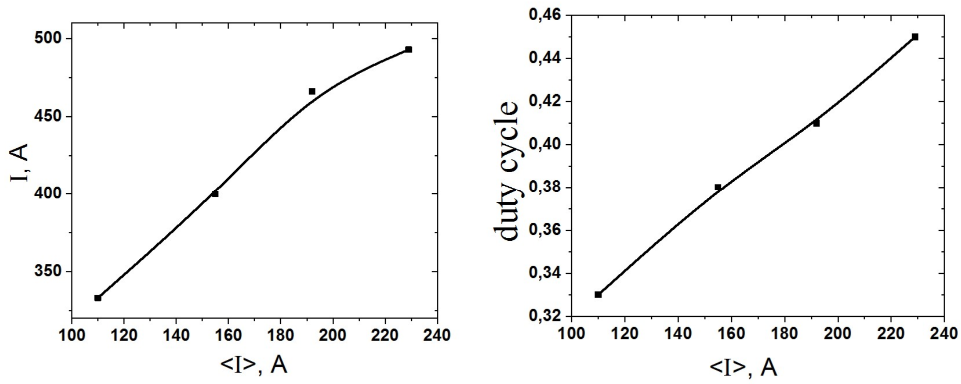

Fig. 3. Dependence of average welding current <I> and momentum current I (a), duty cycle (b)

When switching from stationary to pulsed welding mode (ewm Phoenix Pulse 501), the current-voltage characteristic changes as well. There is a superposition of pulses – short-term intervals of large amplitude pulses are imposed on high-frequency pulses (I=447 A, Fig. 4). Thus, to calculate the mean current of the pulse process, the mean values of the average pulse current and the pause were first calculated, and then the average current of the whole process was determined. It should be noted that the shape of the high-amplitude pulse is parabolic. That is, the rise, the peak, and the decline. For this reason, the authors have introduced a correction factor for the whole process average current calculation formula α.

$$I_{av} = \frac{\alpha \cdot I_{pulse} \cdot t_{pulse} + I_{pause} \cdot t_{pause}}{t_{pulse} + t_{pause}} \qquad (2)$$

In this case, the correction factor α in eq.2 was defined as the difference in the squares of the rectangular and parabolic pulse. For this purpose, areas were determined and their ratios were taken $S_{parabolic}/S_{rectangular}=0.84$. A qualitative study of the pulse mode of welding (Fig. 5) made it possible to establish that with the increase of the average welding current (set on the device), the frequency of pulse propagation of a large amplitude increases.

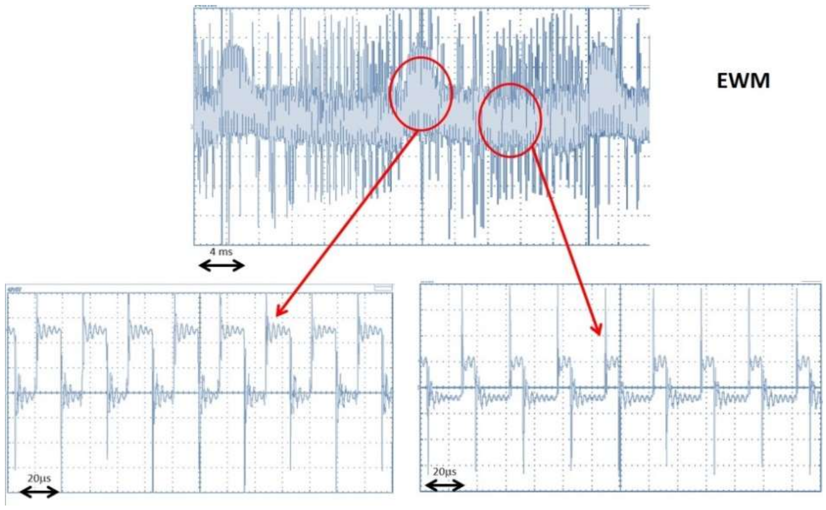

Fig. 4. Welding current waveform for pulse mode (schematic view)
a – overall wave form, b – wave form in pulse, c – wave form in pause

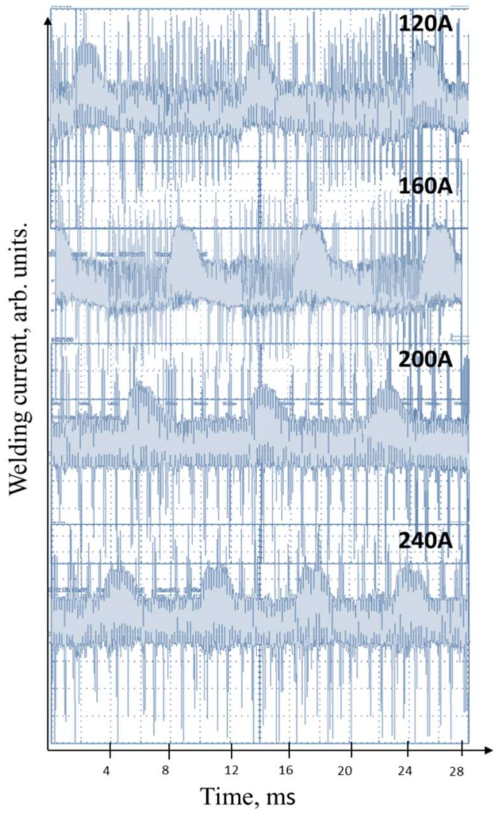

Fig. 5. Waveforms for inverter power supply, pulse welding mode (schematic view)

The quantitative study of the waveforms allowed us to establish the features of the pulse mode. First, the average high-amplitude current has constant characteristics: Iav = 447 A, duty cycle = 0.6, frequency = 58 kHz. In the pause, the average current increases from 72 to 164 A, i.e., the amplitude of the pause current increases, while the average current increases from 120 to 240 A, respectively. In addition, the pause in the pause increases from 0.23–0.4, as well as the process duty cycle increases from 0.19 to 0.36 (Fig. 5). This is achieved by increasing the following frequency from 89 Hz to 153 Hz. According to a study by the authors [12], these frequencies correspond to the optimum, which allows obtaining quality welded joints. If examine the parameter ϕ:

$$\phi = (\frac{I_{pause}}{I_{pulse}}) \cdot f \cdot t_{pause}, \qquad (3)$$

which is equal to $\phi = 0.13–0.23$, we can say that according to [14] these indicators also belong to the optimal ones. That is, the developers of Phoenix Pulse 501 ewm equipment in software that controls the choice of pulse-arc welding modes are pre-set for optimal parameters.

The analysis of welding thermal cycles allowed us to establish the following features: in the case of PC-GMAW, the rate of increase of the metal temperature of the overheating section of the HAZ is greater than in the case of stationary arc welding; in the high-temperature region from 1350°C to 1000°C, the cooling of the metal at the PC-GMAW occurs faster, and in the temperature range less than 1000°C – slower (Fig. 6).

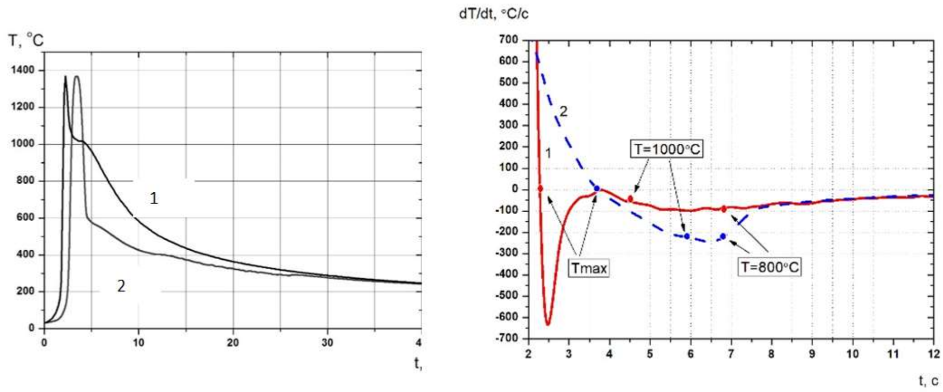

Fig. 6. Welding Thermal Cycles (a) and derivative of WTC (b) for PCGMAW (1) and GMAW (2)

A more detailed analysis of the effect of pulsed welding modes on the cooling rate of HAZ metal is shown in Fig. 7. The above data show that the rate of cooling of the metal in the temperature range of the lowest austenite resistance 600–500°C for PC-GMAW is less than in the case of steady-state arc welding, and $\tau_{8/1}$ has close values. The peculiarities of WTC leakage during pulse-arc welding revealed from the graph of the derivative (Fig. 7 made it possible to establish that the rate of cooling of the metal at the HAZ sections, which are heated to temperatures of 1000°C are higher than during the steady-state arc welding process. Due to this, martensitic components appear in the structure.

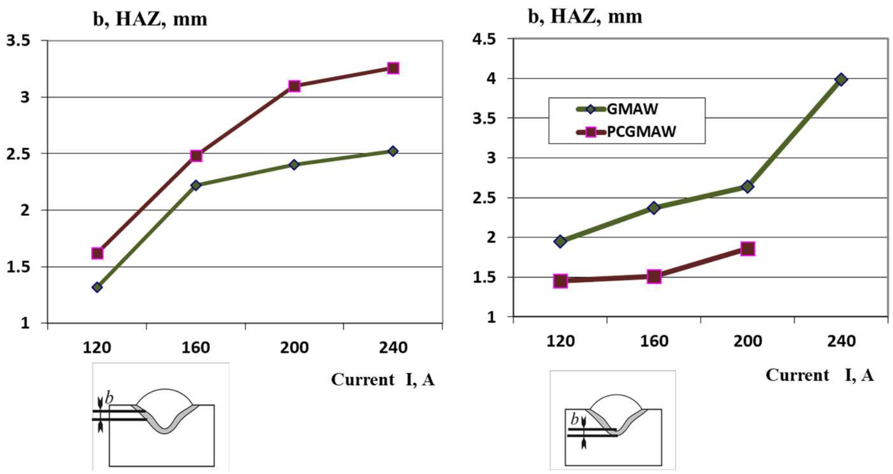

Fig. 7. Effect of the average welding current (during GMAW and PCGMAW) on the HAZ width (b, mm)

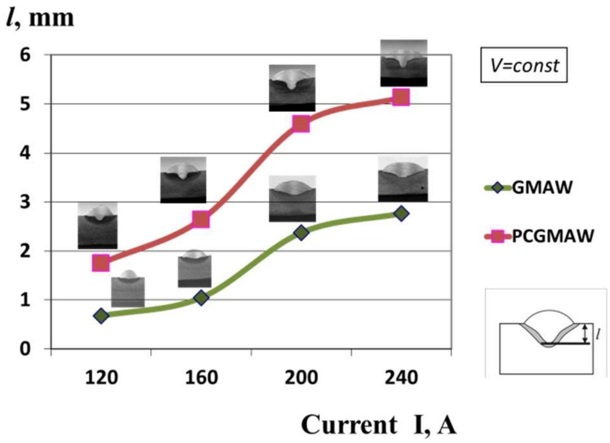

Fig. 8. Effect of the average welding current (during GMAW and PCGMAW) on the penetration depth (*l*) and on the shape of the seam. Welding speed V=const

In HAZ, where the metal is heated to temperatures below 1000°C, the rate of cooling of the metal is lower than with steady-state arc welding. This contributes to the flow of diffusion processes during structural transformations and as a consequence of the formation of mixed bainitic-martensitic structure.

The change in cooling conditions observed during the transition from steady-arc welding to pulsed arc welding suggests that, in this last welding process, high-strength steels with Ra>600MPa will get a more favorable structure with higher stability in the HAZ metal and resistance to cold crack formation. Work in this direction will be the result of further researches.

The appearance of the surfacing made by stationary and pulsed arc welding differs [1]. When comparing the steady-state and pulsed-arc welding modes, it is clearly seen that with pulsed-arc welding the seam is more uniform without traces of splashing. Measurement of the loss of metal on the spray showed that in the case of pulsed arc welding it decreases by an order of magnitude, from 0.7% at stationary to 0.07% at pulsed arc welding.

Analysis of the cross-section of the welds performed in different modes showed that the depth of penetration during pulsed arc welding increases in comparison with stationary welding in the same modes (Fig. 8). The form of seam penetration during pulsed arc welding differs significantly from the process performed by a steadily burning arc. With regard to the depth of penetration, in general, with the increase of the welding current, it increases, but in the case of pulsed arc welding, the depth of penetration is almost twice more than in the case of standard arc welding.

Quantitative analysis showed that with increasing welding current, the width of the seam also increased. The nature of the change in this value is the same for both steady-state arc welding and pulsed arc welding. A similar dependence is observed for the height of the seam. The magnitude of the HAZ under the fungus is comparable for both types of welding and at the root of the HAZ seam is less by 40 percent for pulsed arc welding (Fig. 7).

Thus, the paper shows a significant difference in the welding and technological characteristics of the pulse-arc process from stationary welding. These differences make it possible to change the geometrical parameters of the weld seam and effectively regulate the heat input. On the basis of the conducted researches we can make the following conclusions.

Conclusions

It is established that the change in the welding current is complex in the PC-GMAW, namely: on a high-frequency pulse signal (60 kHz) are imposed impulses of low-frequency current (from 90–150 Hz). The change in the values of the mean welding current at PC-GMAW is achieved by increasing the pause current and the frequency of high-amplitude current pulses. It is shown that the PC-GMAW allows reducing the amount of metal splashing, to increase the depth of penetration (almost 2 times) compared to stationary welding. At the same time, the cooling rate of HAZ metal in the temperature range 600–500°C decreases almost 1.5 times, which allowed to reduce the width of HAZ by 40%.

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