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INFLUENCE OF PULSED-ARC WELDING CONDITIONS ON CHANGE OF PARAMETERS OF WELD AND HAZ OF WELDED JOINTS AND MECHANICAL PROPERTIES OF LOW-ALLOY STEELS

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Pulsed-arc welding is characterized by a periodical changing in arc power and, due to its features, it allows solving complex technological problems while creating unique structures, increasing efficiency of welding processes while maintaining a high level of physical and mechanical properties of welded joints. There are many manufacturers of welding equipment, that introduced the idea of using pulsed welding in their production, but data on the impact of pulsed-arc welding on parameters of welds have a different nature. For the successful application of pulsed-arc welding in modern production, it became necessary to study the influence of pulsed-arc welding conditions on the parameters of welds and HAZ as compared to welding using stationary-burning arc, performed using low-alloy welding materials. 20 Ref., 7 Figures.

Keywords: pulsed-arc welding, pulsating arc welding, heat-affected zone, low-alloy welding materials

Pulsed-arc welding is qualitatively different from conventional shielded-gas welding, as well as from manual arc welding at modulated current [1–5]. This process finds ever more application in the manufacture of welded structures from aluminium alloys, titanium and structural steels with the strength of up to 500 MPa [6, 7]. This is explained by the fact that pulsed-arc welding expands the possibilities of controlling the processes of melting and transfer of electrode metal in different spatial positions, improves the formation of welds, reduces the volume of stirring of electrode metal with the base metal and the size of the heat-affected zone [8–16]. This is connected namely with the fact that such well-known companies as Fronius (Austria), Böhler (Germany), ESAB (Sweden), EWM (Germany) and others pay a considerable attention in their activities to the development and manufacture of equipment for realization and expansion of the pulsed-arc welding process in shielding gases. The technical literature covers the influence of PAW parameters on the thermal processes occurring in HAZ metal of welded joints much less, as they affect the structure and mechanical properties of this metal, its resistance to the formation of cold cracks and brittle fracture, etc. In addition, there are differences in the control of pulsed-arc welding modes in different manufacturers. Namely, the uncertainty of these issues hinders the use of pulsed-arc welding in shielding gases in the manufacture of metal structures from the steels that are sensitive to thermal processes and prone to hardening. Therefore, at this stage, the study of the influence of pulsed-arc welding modes using EWM Phoenix Pulse 501 power source on the formation of the weld, thermal welding cycles and mechanical properties of welded joints of low-alloy steels were carried out.

Procedure of experiment. To solve the task set in the work at the first stage, surfacing was performed with a low-alloy welding wire G3Si1 with a diameter of 1.2 mm, which is an analogous to the well-known wire of grade Sv-08G2S. Surfacing was performed on 10 mm thick plates made of 09G2S steel. The sections were made of surfacing plates, on which the parameters of welds and HAZ were measured. The geometric parameters of the welds were determined by digitizing and using special software Axio Vision 4.6. To detect HAZ, the sections were subjected to macroetching with a solution of ferric chloride.

The record of TWC of HAZ overheating area was carried out with the use of chromel-alumel thermocouples of 0.5 mm diameter, while were installed in HAZ region, which were heated to the temperature of 1200 °C.

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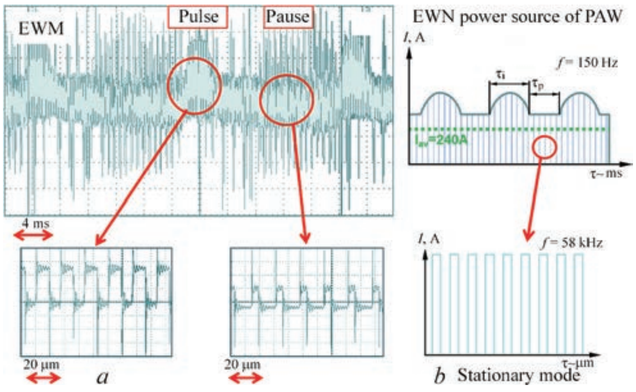

Figure 1. Oscillogram of welding current for pulsed mode: *a* — oscillogram in real time; *b* — schematic image

The key parameters of pulsed-arc welding include: pulse current (I_{pulse}), pause current (I_{pause}), pulse time (t_{pulse}), pause time (t_{pause}). To simplify the characteristics of the pulse process, the following fixed auxiliary parameters were accepted: mean (I_m) and effective welding current (I_{eff}), duty cycle (δ) and frequency (f). To evaluate the influence of pulsed-arc welding modes on the weld parameters, the following conditions were selected: welding current I_m = 120, 140, 160, 180, 200, 220 A, voltage U = 21, 22, 24, 26, 28, 30 V, welding speed 15 m/h, shielding gas is mixture Ag + 18 % CO_2. As a current source, an inverter-type rectifier of the EWM Phoenix Pulse 501 was used, which will provide a different frequency of pulse passage. Such parameters of pulsed-arc welding as duty cycle and pulse frequency for the EWM Phoenix Pulse 501 power source during operation in the pulse mode are programmed by the manufacturer, the user has the ability to control only the value of the mean welding current. Therefore, in the future we manipulate the value of the mean welding current during pulsed-arc welding. It should be noted that with an increase in the mean welding current the frequency f increases from 89 to 153 Hz and the duty cycle δ grows from 0.2 to 0.36.

To determine the welding and technological characteristics (Figure 1) of the current source, a digital oscilloscope UTD2000CEX-II was used, which allows fixing the volt-ampere characteristics within wide ranges. To record the oscillograms, a shunt 75ShSM with a resistance of 150 μOhm was used, which allows recording the welding current of up to 500 A.

Pulsed-arc welding ($f \geq 25$ Hz) and pulsating arc welding ($f \leq 25$ Hz) are distinguished by the frequency of pulses. The optimal pulsation modes were selected using a pulsating arc. In this case, the welding conditions were as follows: welding pulse current I_{pulse} = 140 A, pause current (base current) was 80 % of the pulse current I_{pause} = 112 A; voltage on the arc in the pulse U_{pulse} = 22 V, voltage on the arc in the pause U_{pause} = 18 V, welding speed v_w = 15 m/h, moreover, the pulse time t_{pulse} and pause time t_{pause}, as well as current in the pause were varied.

At the second stage, to evaluate the effect of pulsed-arc welding on the mechanical properties of welded joints of low-carbon steels S460M and 14Kh2GMR the specimens were welded to. Mechanized welding in shielding gases (Ag + 18 % CO_2) from joints of steel S460M and 14Kh2GMR of 16 mm thickness with a V-shaped edge preparation using the wire of a solid section G3Sil and Sv-10KhN2GSMFTYuA with a diameter of 1.2 mm, respectively. The root passes during welding of these steels were produced on a copper substrate. Welding using the conventional process (by arc that burns stationary) was performed on the following conditions: I_w = 180–200 A, U_a = 26 V, v_w = 15–18 m/h. The conditions of automated pulsed-arc welding were as follows: I_m = 220–240 A, U_a = = 26–28 V, v_w = 14–21 m/h.

In order to conduct mechanical tests and determine the impact toughness of HAZ metal, standard specimens were prepared. For the static (short-term) tensile tests, the specimens of type II were mechanically manufactured of steel in accordance with GOST 6996–96 (3 specimens for each cooling rate). The tests were performed according to GOST 6996–66 at a temperature of 20 °C. The impact toughness was determined during tests of Charpy specimens with a sharp notch (GOST 9454–78) at the test temperatures of –40 °C. The resistance to cold crack formation was determined using technological Tekken specimens.

Obtained results and their discussion. *Pulsed-arc welding.* When comparing the stationary and pulsed-arc welding modes, it is clearly seen that in pulsed-arc welding the weld bead is more homogeneous and uniform without traces of spattering. The measurements of metal losses on spattering showed that in pulsed-arc welding they decrease by an order of value, from 0.7 % during the stationary process to 0.07 % during pulsed-arc welding.

Analysis of the cross-section of the deposits (Figure 2) performed under different conditions showed that the penetration depth during pulsed-arc welding increases as compared to the stationary welding process on the same conditions. Thus the shape of weld penetration in pulsed-arc welding considerably differs from the process which was performed by a stationary-burning arc.

The quantitative analysis showed that with an increase in welding current, the width of the weld also increases. The nature of the change in this value is the same for welding using a stationary-burning arc, as well as for pulsed-arc welding. The similar regularity is observed for the height of the weld. As for the penetration depth, in general, with an increase in welding current, it increases, but in the case of pulsed-arc welding, the penetration depth is almost twice higher than in the case of stationary arc welding (Figure 3). Also in pulsed-arc welding, the cross-sectional area of the weld exceeds these indices for welding using a stationary-burning arc. The value of HAZ under the mushroom-shaped section is comparable for both

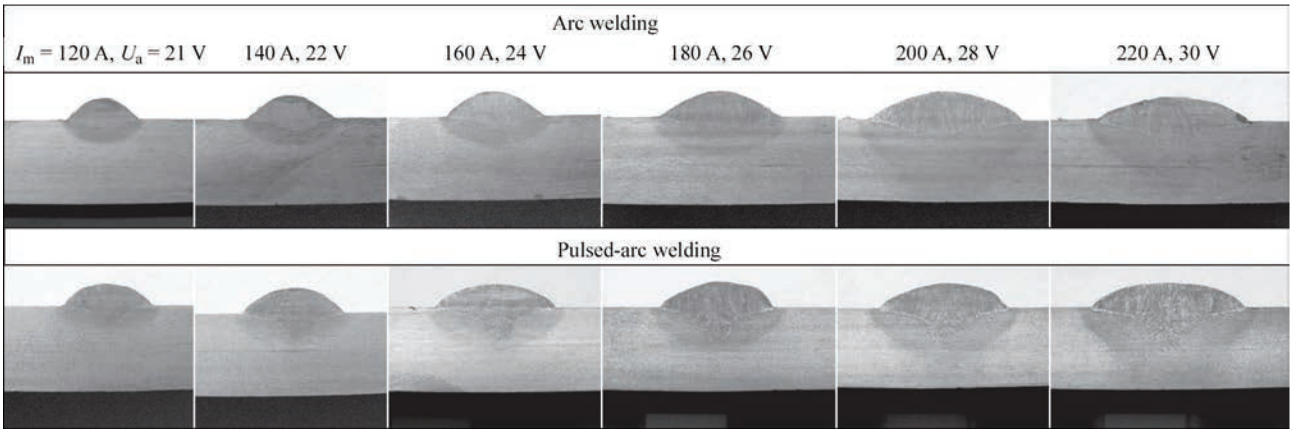

Figure 2. Appearance of macrosections

types of welding, and in the weld root of the HAZ during pulsed-arc welding it is lower (Figure 3).

Pulsating arc. According to the experiment data, it was found that with an increase in the pause current, the width of the weld increases, here to smaller values of the duty cycle larger values of the weld width correspond (Figure 4). The height of the weld increases uniformly with an increase in the pause current. The change in the penetration depth has similar regularities, i.e. it increases with an increase in the pause current. The change in HAZ parameters under the mushroom-shaped section has a monotonous nature. The lower duty cycle corresponds to large values of HAZ width. It is important to note that the average HAZ values under the mushroom-shaped section are lower than during welding using a stationary-burning arc and pulsed-arc welding. The similar regularities are observed for HAZ both in the weld root (Figure 4, *b*) as well as in the surface of the weld.

At the welding conditions at a pulse current I_{pulse} = = 140 A and the pause current I_{pause} = 112 A (fixed pulse time is 0.5 s) with an increase in the pause time, i.e. with a decrease in the frequency *f* and duty cycle δ, the weld height increases, the weld width decreases slightly and the width of HAZ decreases, and the penetration depth at t_{pause} = 0.5 increases, and then almost does not change. In the case of fixing the pause time (0.5 s) and increasing the pulse time, i.e. with an increase in frequency *f* and duty cycle δ, the penetration depth also initially increases, and then stabilizes, but to confirm this fact the further investigations are required. The width of the HAZ varies in a nonlinear form, but in the case of a fixed pulse time it is lower than in the case of stationary-burning arc welding. In the case of fixing the pause time and increasing the pulse time, the width of

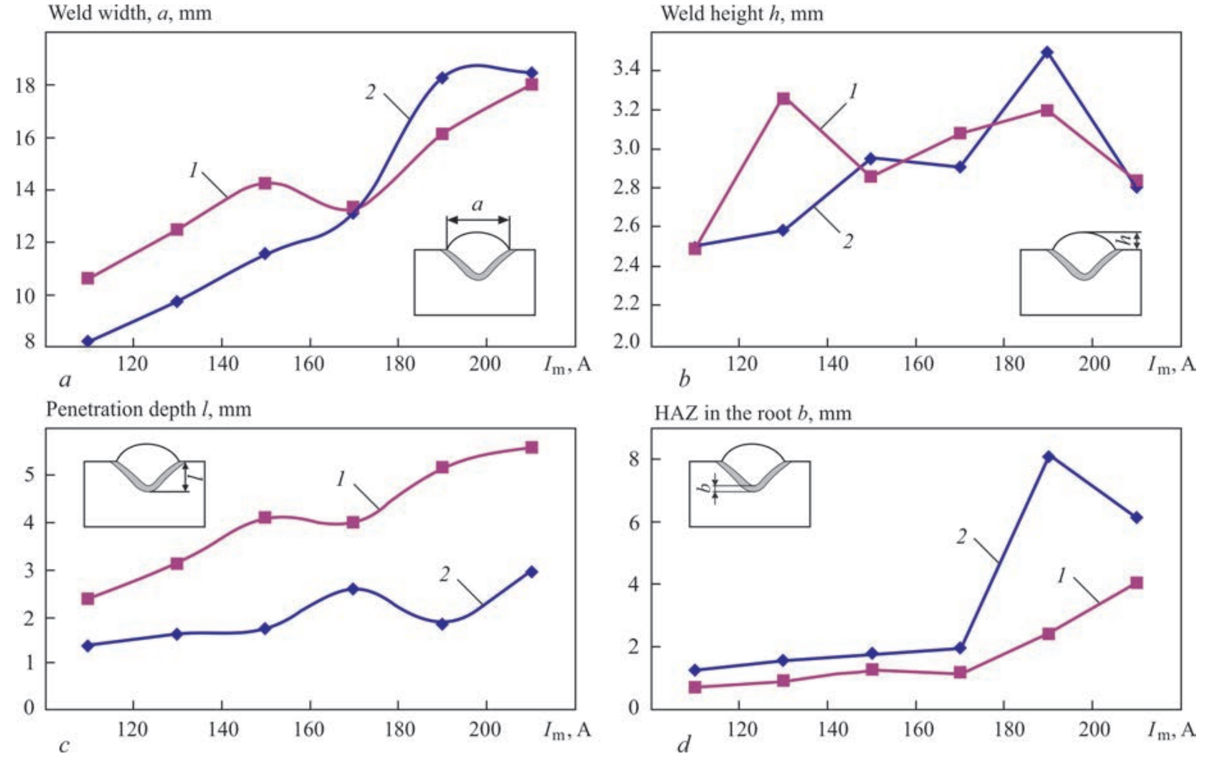

Figure 3. Quantitative characteristics of parameters of welds produced by pulsed-arc and arc welding: *1* — pulsed-arc; *2* — arc

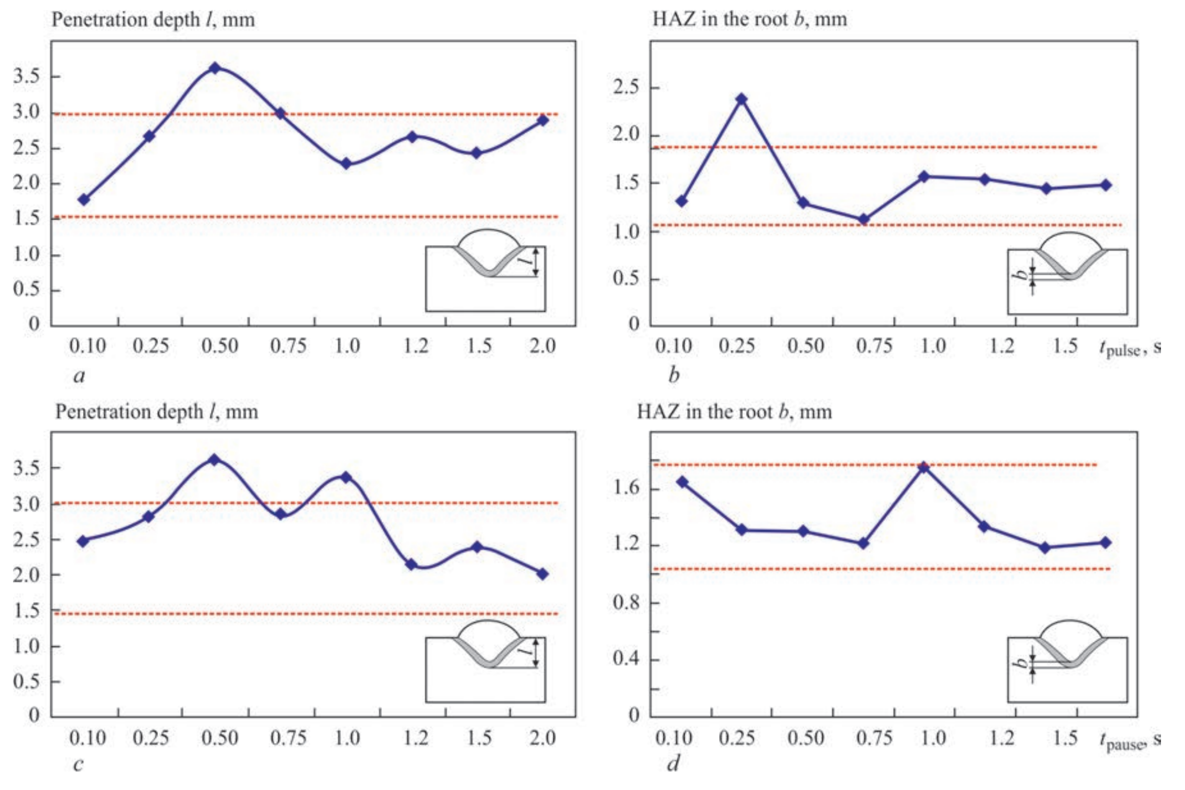

Figure 4. Quantitative characteristics of parameters of welds produced by pulsating arc welding: *a*, *b* — pulse time is fixed t_{pulse} = 0.5 s; *c*, *d* — pause time is fixed t_{pause} = 0.5 s

the HAZ is larger than for pulsed-arc welding and lower than for the welding using a stationary-burning arc.

The analysis of thermal cycles of welding allowed establishing the following features: in pulsed-arc welding the rate of growing temperature of metal of an area of HAZ overheating is higher than in the case of welding by a stationary arc; in the high-temperature range from 1350 to 1000 °C, the cooling of the metal during pulsed-arc welding is faster, and in the temperature range lower than 1000 °C, it is slower (Figure 5). A more detailed analysis of the influence of pulsed welding modes on the cooling rate of HAZ metal is shown in Figure 6. From the given data it is seen that the cooling rate of the metal in the temperature range of the lowest resistance of austenite of 600–500 °C for pulsed-arc welding is 1.5 times lower than in the case of stationary arc welding, and the time of cooling metal in the temperature range of 800–100 °C $\tau_{8/1}$ has the similar values. Peculiarities of running TWC during pulsed-arc welding, revealed from the diagram of the derivative (Figure 5), confirmed that the cooling rate of the metal in the areas of HAZ, which are heated to the temperatures higher than 1000 °C is higher than during welding with the arc, which burns stationary. In HAZ, where the metal is heated to the temperatures lower than 1000 °C, the cooling rate of the metal is lower than during welding using a stationary-burning arc. This contributes to the diffusion processes during structural transformations and, as a consequence, the formation of a mixed bainitic-martensitic structure.

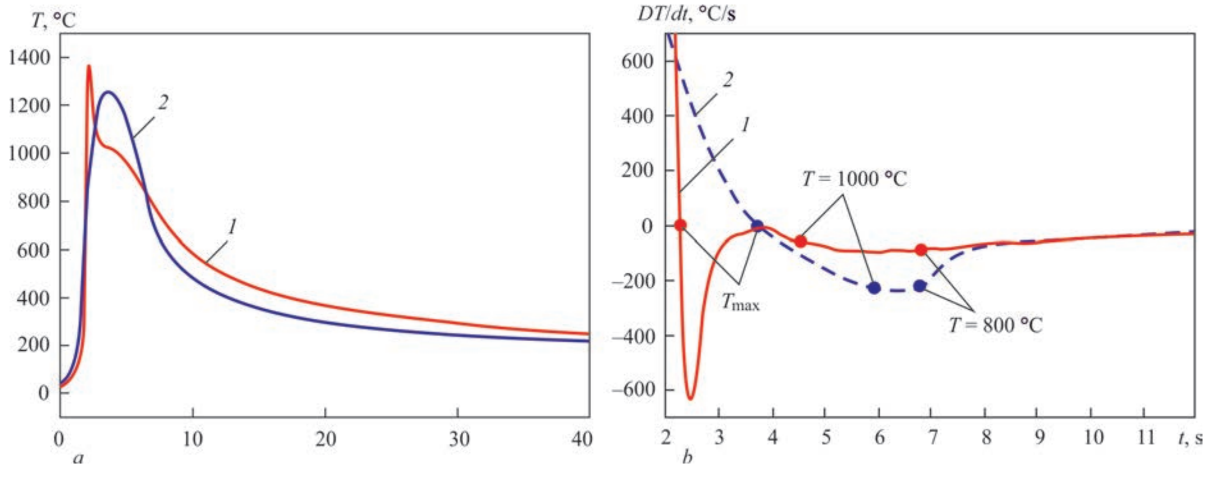

Figure 5. Thermal welding cycles (*a*) and rate of temperature change (*b*) for pulsed-arc welding (*1*) and arc welding (*2*)

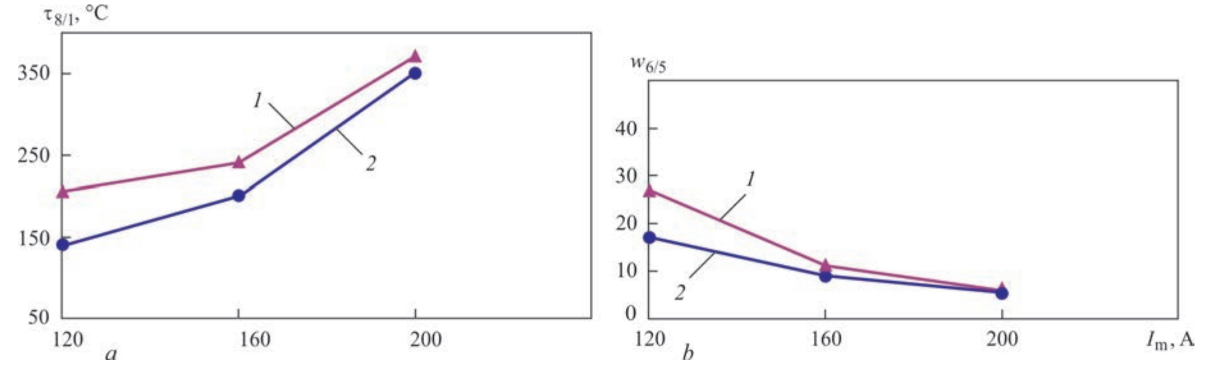

Figure 6. Change of time (*a*) and rate (*b*) of cooling of area of overheat of HAZ metal in pulsed-arc welding (*2*) and welding using stationary arc (*l*) at a rate of 15 m/h

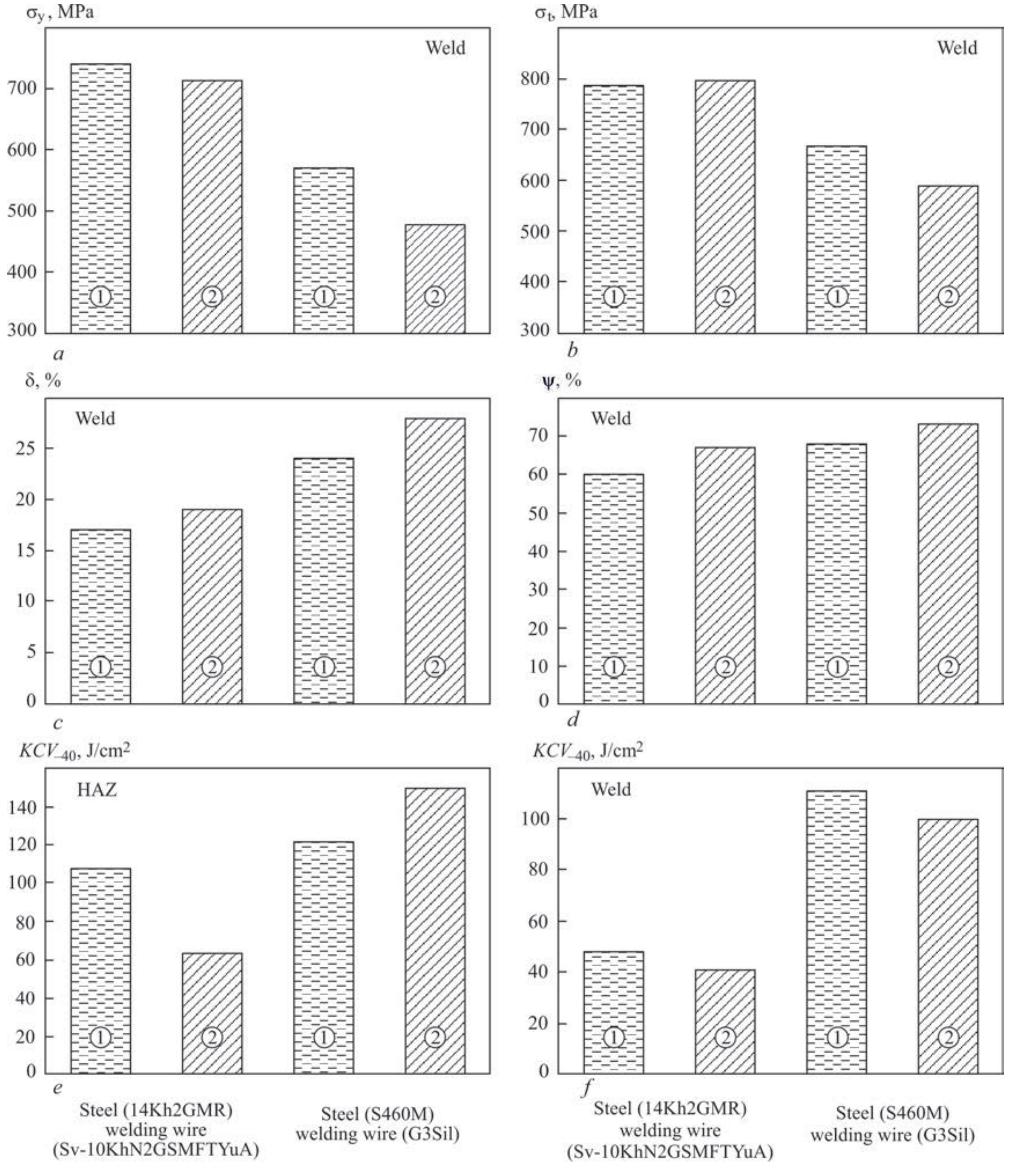

Figure 7. Mechanical properties of welded joints of low-carbon high-strength steels 14Kh2GMR and S460M during pulsed-arc welding (*1*) and arc welding (*2*)

The change in cooling conditions observed during the transition from stationary-burning arc welding to the pulsed-arc welding suggests that in this process of welding in the HAZ metal of high-strength steels with $\sigma_{0.2}$ > 600 MPa will form a more favorable structure with a high stability to cold crack formation and to brittle fracture. The work in this direction will be the result of our further investigations.

The mechanical properties of welded joints are shown in Figure 7. Studies of the effect of pulsed-arc welding on the mechanical properties of welded joints of low-carbon high-strength steels of grades S460M and 14Kh2GMR showed that pulsed-arc welding allows obtaining higher values of static strength of the weld metal while maintaining a high level of ductility. Moreover, the values of impact toughness KCV_{-40} at the test temperature of –40 °C for both weld metal as well as HAZ metal exceed the values obtained by welding using a stationary-burning arc. Thus, under the conditions of pulsed-arc welding the best values of operational characteristics are reached, and the values of impact energy exceed the requirements of EN 10025-2 $KCV_{-20} \geq 27$ J.

The results of tests of welded joints, which were produced using Tekken technological specimens, testify to a sufficiently high resistance to the formation of cold cracks of S460M steel both in pulsed-arc welding and in arc welding without heating. For stronger steels, such as 14Kh2GMR, it is possible to increase the resistance of welded joints to a delayed fracture in both pulsed-arc welding and stationary arc welding, possibly due to a preheating to the temperatures of 90–100 °C.

Conclusions

Comprehensive investigations of the influence of pulsed-arc welding modes using the EWM Phoenix Pulse 501 power source on the formation of the weld, thermal welding cycles and mechanical properties of welded joints of low-alloy steels established that:

● pulsed-arc welding in the specified ranges of frequencies and duty cycle allows reducing the amount of metal spattering, the width of the heat-affected zone, increasing the penetration depth (almost 2 times) as compared to stationary-burning arc welding. The cooling rate of the HAZ metal in the temperature range of 600–500 °C is reduced by almost 1.5 times;

● use of pulsating arc welding allows expanding the possibilities of controlling the weld formation and increasing the width of the weld and reducing the width of the HAZ as compared to welding using a stationary-burning arc;

● it is shown that the metal of welds and HAZ of welded joints of steels S460M and 14Kh2GMR produced by pulsed-arc welding, have a sufficient resistance to cold crack formation and a higher static strength while maintaining a high level of ductility of the weld metal.

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