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EFFECT OF PULSED-ARC WELDING MODES ON THE CHANGE OF WELD METAL AND HAZ PARAMETERS OF WELDED JOINTS PRODUCED WITH Sv-08Kh20N9G7T WIRE

V.D. POZNYAKOV, A.V. ZAVDOVEEV, A.A. GAJVORONSKY, A.M. DENISENKO and **A.A. MAKSYMENKO**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

Pulsed-arc welding is characterized by periodically varying arc power and due to its peculiarities it allows solving complex technology issues in development of unique structures, increasing the efficiency of welding processes, and depositing corrosion-resistant alloys on steel. At present, there is a great number of welding equipment manufacturers, who have introduced the ideas of pulsed welding application in their production. However, the data on the effect of pulsed-arc welding on the welding thermal cycles are of a fragmentary nature, and, therefore, it is difficult to compare the thermal cycles typical for stationary and pulsed-arc welding. In welding of high-carbon steels there is a problem of reducing weld metal mixing with base metal and the resulting increase of welded joint cold cracking resistance. Successful application of pulsed-arc welding for solution of the above-mentioned problems necessitated performance of comparative investigations of the effect of the modes of pulsed-arc welding on the parameters of welds, HAZ and welding thermal cycles in comparison with stationary arc welding produced with high-alloy welding consumables. This was the main aim of the investigations, the results of which are given in this paper. 31 Ref., 8 Figures.

Keywords: *pulsed-arc welding, pulsating-arc welding, welding thermal cycle, heat-affected zone, high-alloy welding consumables*

Pulsed-arc welding (PAW) is characterized by periodically changed power of the arc, and it has been known since 1940s. Welding process with periodically changed arc power was proposed for the first time in the USSR in 1953 by Zajtsev M.P., for welding steel sheets, in order to reduce the heat losses [1]. However, the first mention of pulsed welding in the world dates back to 1932. This kind of welding was invented by engineer Earl J. Ragsdale in Budd Company in 1932 for stainless steel welding and was used to manufacture diesel railway train Pioneer Zephyr [2]. Pulsed-arc welding in this case allowed 3–8 times increase of labour efficiency, compared to nonconsumable electrode welding, and considerable reduction of deformation during its performance at practically the same quality of welded joints. Different authors called welding with periodically changing power of the arc in different ways: pulsed-arc, pulsating-arc, modulated current, and nonstationary arc welding. However, the common name of all the above methods is modulated current welding (MCW) [3]. MCW mainly allows ensuring a controllable transfer of electrode metal, increasing arcing stability, reducing spatter, as well as controlling the rate and direction of weld pool metal solidification, regulating the thermal impact on the heat-affected zone (HAZ) of welded joints. By pulse repetition rate MCW is divided into PAW ($f \geq 25$ Hz, Figure 1, *a*) and pulsating-arc welding ($f < 25$ Hz, Figure 1, *b*).

PAW [4–6] provides controllable transfer of electrode metal, the main condition of which is drop detachment by each current pulse and possibility of controlling their transfer frequency. It is believed that in gas-shielded welding, the pulse duration should be sufficient for detachment of the electrode metal drop. In the case of drop detachment at the current close to the amplitude value, metal transfer is accompanied by greater spatter [7]. Minimum spattering losses and controlled metal transfer at welding in all the positions ensure drop detachment at the end of pulse action. The main advantages of PAW include its ability to be used for critical structures from different steel grades, aluminium, copper, nickel alloys and titanium of 1 mm and greater thickness.

Owing to high spatial stabilization of the arc and possibility of application of greater electrode extension, this process can be used with success, both for welding thin metal, and for thick-walled structures. PAW in an intermediate link between spray transfer and short arc welding that makes it ideal for weld-

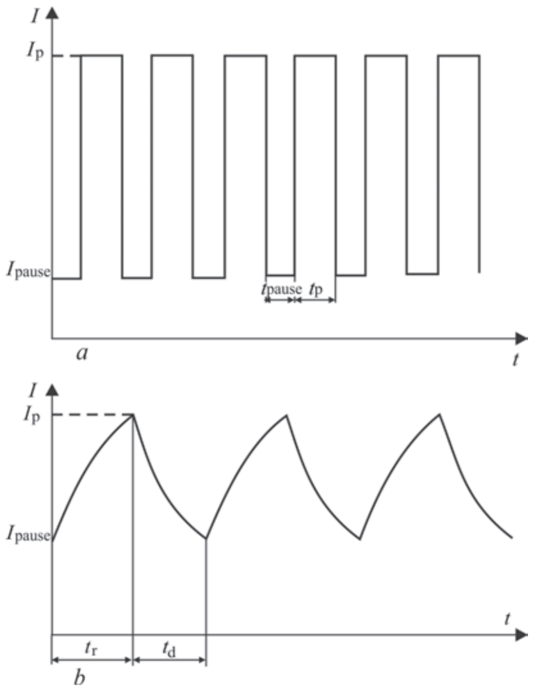

Figure 1. Change of current in time at PAW ($f \geq 25$ Hz) (*a*) and pulsating-arc welding ($f < 25$ Hz) (*b*): t_p — pulse time; t_{pause} — pause time; t_r — current rise time; t_d — current drop time; I_p — pulse current; I_{pause} — pause current

ing thick metal, where heat input control is required. PAW, owing to its features, allows solving complex technological issues at development of unique structures, increasing the efficiency of the welding processes, and depositing corrosion-resistant alloys on steel [8]. At present there exists a great number of welding equipment manufacturers, who introduced the ideas of pulsed welding application in their production. Swedish Company ESAB developed Aristo 500 power source for PAW [9] with program control, which automatically assigns the welding modes, according to synergistic dependencies. US Company Hobart developed Ultra-Arc 350 system for consumable electrode PAW [10]. This system has nine programs, envisaging welding of carbon and stainless steels in a mixture of gases with 0.8 and 1.2 mm wires. PWI developed I-169 power source for PAW with smooth regulation of the parameters of current pulses of a stepped form [11].

An important condition of the stationary nature of running of PAW process is the optimum combination of the pulse and pause parameters [8, 12–19]. In view of the fact that the number of variable parameters at PAW is considerable, selection of their optimum combination is a quite labour-consuming process and it includes a large number of trials and errors [20]. General recommendation for selection of an optimum combination of PAW parameters is transfer of one drop per pulse [8, 12]. This condition, which is the criterion of metal transfer, can be expressed by the following relationship [12, 21]:

$$D = I_p^n t_p, \qquad (1)$$

where D is the constant, depending on drop volume, welding wire composition and diameter; exponent «n» has the average value of 2.

If values I_p/I_p are small, then the energy of one pulse is insufficient for drop detachment. In this case, the drop can separate from the electrode under the impact of gravitation forces. In the case, when the products of pulse current and time have large values, two or three drops can separate per one pulse, and the stability of the welding process is disturbed. Minimum pause current is selected so that the arc was not extinguished during the pause. Modern power sources use the above-listed recommendations for PAW in the programmed modes. As a rule, operator instrument panels show average values of current, which is determined by the following equation [8, 12, 22]:

$$I_{av} = \frac{I_p t_p + I_{pause} t_{pause}}{t_p + t_{pause}}. \qquad (2)$$

In this case, it is possible to compare PAW modes with those of stationary welding, welding heat input is directly proportional to welding current.

One of the most important characteristics, determining the welded joint properties, is the welding thermal cycle (WTC), which determines the HAZ metal structure. Knowing the features of WTC at pulsed-arc welding mode it is possible to predict formation of the structure and properties of welded joint HAZ. So, for instance the authors of [12, 23–25] report that PAW is characterized by a lower level of heat input, thus ensuring penetration comparable with spray transfer. K. Tsen [26], measuring the welding thermal cycles for the stationary and pulsating modes, at 2 mm distance from the fusion line, showed that in the latter case smaller maximum temperature of metal heating is achieved. This fact can be an indication, in the opinion of the authors of [26], of smaller heat input. As the metal heating temperature is smaller in the case of the pulsed process at the same distance from the fusion line, this leads to an indirect conclusion that the HAZ width in this case was smaller, and that the rate of metal cooling in the high-temperature region was higher, compared to the process, which was performed by a stationary arc. The effect of the pulse repetition rate and fullness on the metal cooling rate is considered in [27]. It is shown that in the range of the change of repetition rate from 60 up to 120 Hz and of fullness from 20 up to 30 %, the cooling rate practically does not change, either in the high-temperature, or in the low-temperature regions. Values of pulse repetition rates and fullness were selected, proceeding from the fact that these ranges of PAW parameters cover a wide area of practical application [28]. It should be also noted that based on WTC data for the pulsed mode, a certain «tooth» (jump) in metal temperature variation is observed in the high-temperature region that, in all probability, is attributable to the features of pulsed heat input into the weld pool. Study of WTC in the case of pulsating-arc welding [22, 29] showed that in the low-temperature range the rate of HAZ metal cooling is slowed down, compared to the stationary mode, and in the high-temperature range it is accelerated. Here, in the case [29] of arc pulsation frequency rising from 0.5 up to 10 Hz, the rate of HAZ metal cooling becomes the same, as in the case of stationary welding, that is indicative of irrationality of further increase of pulsation frequency.

It should be also noted that the data on PAW effect on the welding thermal cycles are of a fragmentary nature and, therefore, it is difficult to make a comparison between the thermal cycles, characteristic for welding by a steadily burning and pulsed arc. A similar situation is observed in investigations, dealing with variation of weld parameters [30, 31]. The works mainly give comparison of weld parameters at different variants of pulsed or pulsating welding, whereas comparison with similar results for stationary arc welding is absent. Such data are required for understanding the conditions, under which stationary arc welding can be replaced by PAW, in order to increase the productivity and improve product quality. For performing tasks such as welding of high-strength fine-grained steels, it was necessary to solve two mutually exclusive problems of improvement of the process productivity and ensuring the fine-grained structure in the HAZ metal, as well as good penetration of the weld root. Moreover, in welding high-carbon steels, the problem arises of reducing weld metal mixing with base metal and this way increasing welded joint resistance to cold cracking. Thus, successful application of PAW in solving the above problems necessitated performance of comparative studies of the influence of PAW modes on the parameters of welds (width, reinforcement height, penetration depth), HAZ and WTC, compared to stationary arc, performed earlier by high-alloy welding consumables. This was the main purpose of investigations, the results of which are given in this paper.

Experimental procedure. In order to solve the problem defined in the work, beads were deposited by HORDA 307Ti high-alloyed welding wire, which is an analog of the known wire of Sv-08Kh20N19G7T grade. Wire of 1.2 mm diameter was used. Deposition was performed on 10 mm plates from 09G2S steel. Plates with the deposited bead were used to prepare sections for performing measurements of weld and HAZ parameters. To reveal the HAZ, the sections were subjected to macroetching by a solution of ferric chloride. WTC of the HAZ overheated zone was recorded, using chromel-alumel thermocouples of 0.5 mm diameter. The thermocouple was mounted in the HAZ area, which was heated up to the temperature of 1200 °C.

To assess the effect of PAW modes on weld parameters the following modes were selected: welding current I = 120, 160, 200, 240 A, voltage U = 20, 24, 28, 30 V, welding speed of 15 m/h, shielding gas — a mixture of Ar + 18 % CO_2. Inverter type rectifier of ewm Phoenix Pulse 401 grade was used as the current source, which provides pulse repetition rate of 130 Hz at PAW.

Optimum pulsation modes were selected using a pulsating arc. In this case the welding mode was as follows: pulse welding current I_p = 160 A, pause current (base current) I_{pause} = 80 A; arc voltage in the pulse U_p = 24 V, arc voltage in the pause U_{pause} = 18 V; v_w = 15 m/h. Pulse time t_p and pause time t_{pause} as well as pause current and pulse-to-pause ratio were varied. Values of pause current were as follows: I_{pause} = 60, 80, 100, 120 A; pulse-to-pause ratio was varied from 1.4 up to 2.0, pulse repetition rate was higher than 0.5 Hz.

Results and their discussion. *Pulsed-arc welding.* Appearance of bead deposits, made by stationary welding and PAW, is given in Figure 2. At comparison of stationary and pulsed-arc welding modes one can clearly see, that at PAW the weld bead is more uniform and regular without traces of spattering (Figure 2, *b*). Measurements of metal losses for spatter showed that at PAW it is reduced by an order of magnitude, from 0.7 % at stationary mode to 0.07 % at PAW.

Analysis of the cross-section of the beads deposited in different modes, revealed that the penetration depth at PAW becomes greater, compared to stationary welding in the same modes (Figure 3). The shape of weld penetration at PAW differs significantly from

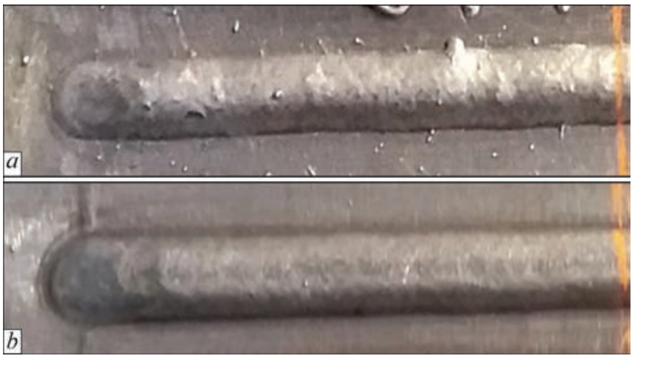

Figure 2. Appearance of the deposited bead: *a* — stationary welding mode; I_w = 160 A; U = 24 V; *b* — pulsed welding mode, I_{av} = = 160 A; U = 24 V, welding speed of 15 m/h in both the cases

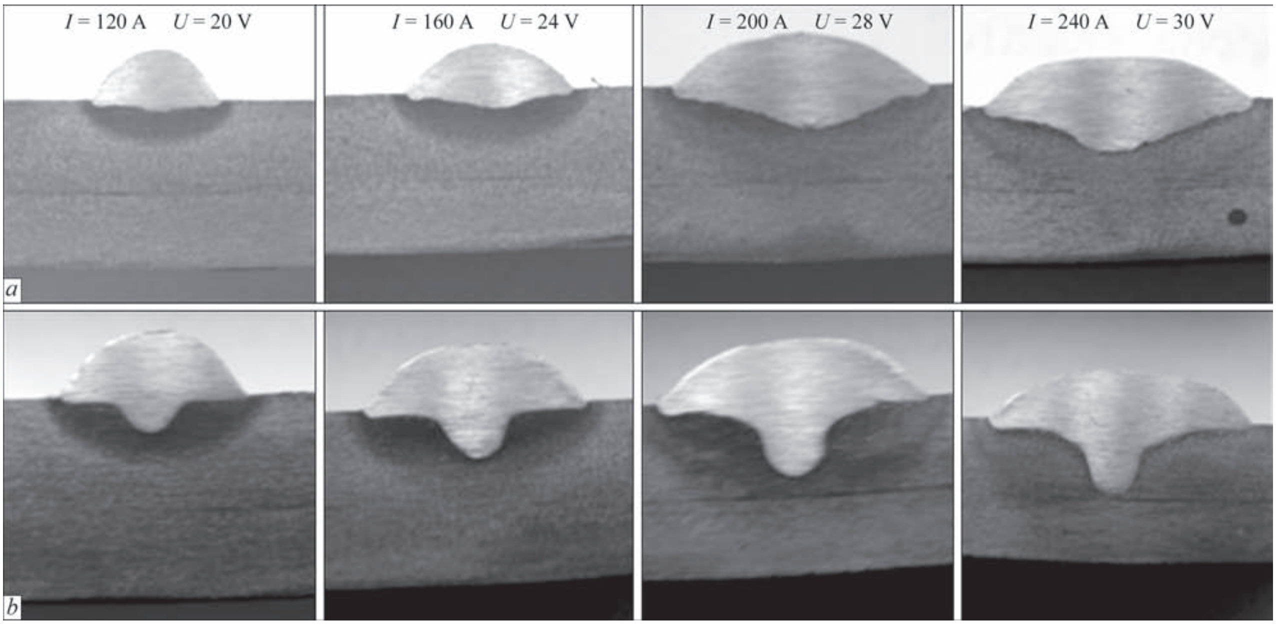

Figure 3. Appearance of the deposits, made by stationary-arc welding (*a*) and PAW (*b*) at the speed of 15 m/h; transverse macrosections

the process, which was performed by stationary arc. Quantitative analysis showed that the weld width also becomes greater with increase of welding current. The nature of variation of this value is the same, both for welding by a stationary arc, and for PAW. A similar dependence is also observed for weld height. As regards penetration depth, on the whole, it increases with increase of welding current, but in the case of PAW the penetration depth is practically two times greater than in the case of stationary arc welding (Figure 4, *a*). At PAW also the weld cross-sectional area exceeds these values for stationary arc welding. HAZ value under the cap is comparable for both kinds of welding, and in the weld root the HAZ is smaller at PAW (Figure 4, *b*). Another important parameter is the width of the HAZ at weld surface, the values of which in PAW at currents higher than 160 A become smaller than in stationary arc welding.

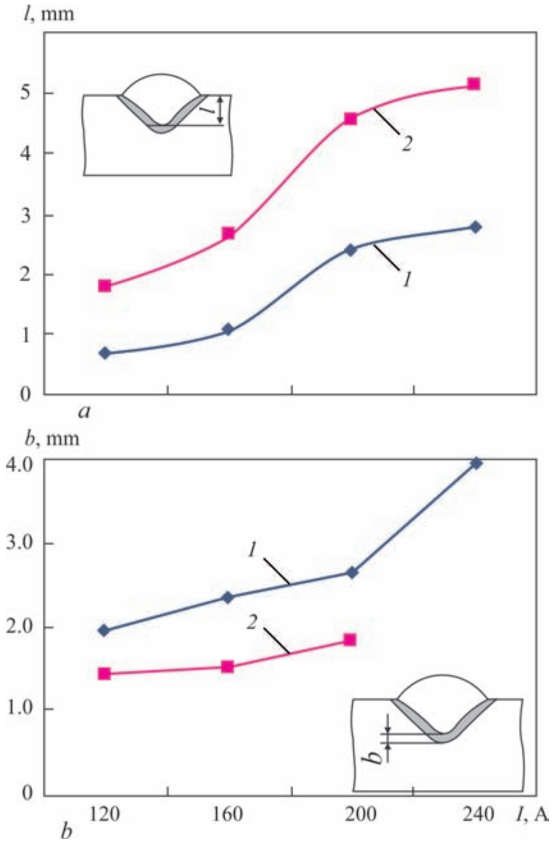

Figure 4. Change of weld and HAZ parameters at stationary-arc welding (*1*) and PAW (*2*), welding speed of 15 m/h: *a* — penetration depth; *b* — HAZ width in weld root

Pulsating-arc welding. At pulse frequency of 0.3 Hz coarse-flaky intermittent weld forms (Figure 5), where the uniformity of bead width along weld length increases with pulse-to-pause ratio reduction. At small frequency of arc pulsations also a nonuniform penetration of the plate is observed (i.e. a marked change of penetration depth along the weld length is found, which reaches 70 %, Figure 5, *b*). Penetration uniformity can be increased by increasing the arc pulsation frequency up to 1 Hz. At constant values of

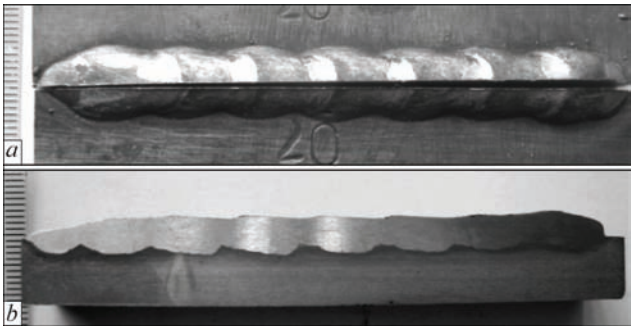

Figure 5. Appearance of deposited bead in the mode of pulsating-arc welding with pulse repetition rate of 0.3 Hz (I_p = 160 A, pulse voltage U_p = 24 V; I_{pause} = 80 A; U_{pause} = 18 V); *a* — top view; *b* — longitudinal section

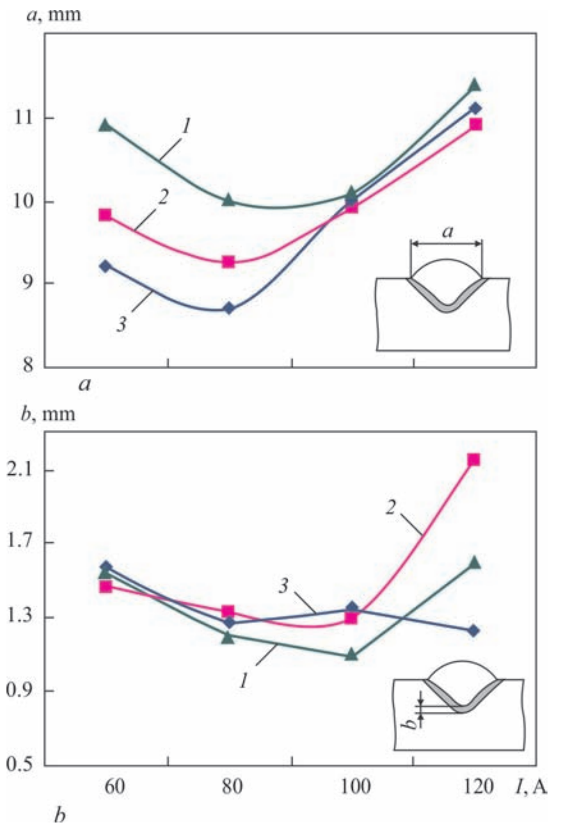

Figure 6. Change of weld and HAZ parameters in pulsating-arc welding, I_p = 160 A; U_p = 24 V (pulse-to-pause ratio: *1* — 1.4; *2* — 1.5; *3* — 2.0): *a* — weld width; *b* — HAZ width in weld root

average current and process pulse-to-pause ratio, also the uniformity of weld bead formation is improved and flakiness becomes smaller with increase of arc pulsation frequency.

Experimental data show that with increase of pause current the weld width first somewhat decreases, and then increases, smaller values of pulse-to-pause ratio corresponding to greater weld width (Figure 6, *a*). Weld height increases uniformly with increase of pause current. Change of penetration depth has some features. At pulse-to-pause ratio equal to two, it changes from 1 mm (that corresponds to penetration depth at stationary welding mode at specified current) up to 1.8 mm. At smaller pulse-to-pause ratio (1.4 and 1.5) the values of penetration depth are in the range of 1.7 mm that is by 70 % greater than in the stationary mode. Weld area increases accordingly with increase of pause current.

Change of HAZ parameters under the cap is of a monotonic nature. Smaller pulse-to-pause ratio corresponds to greater values of HAZ width. It is important to note that average HAZ values under the cap are lower than in stationary arc welding and PAW. Similar regularities are observed also for HAZ, both in the weld root (Figure 6, *b*) and at the weld surface. With increase of pause current the angle of transition to base metal decreases for pulse-to-pause ratio of 2, and practically does not change for smaller values.

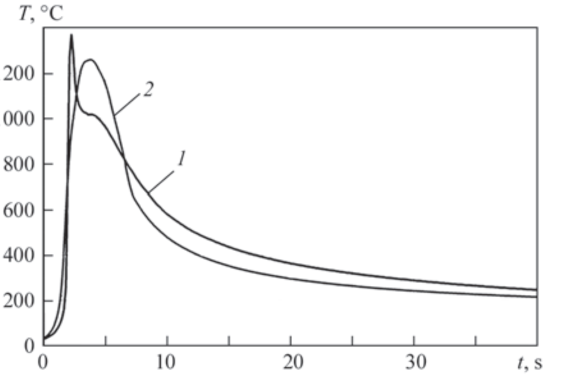

Figure 7. Welding thermal cycles in deposition of high-alloyed welding wire HORDA 307 on 10 mm plates from 09G2S steel: I_w = 120 A; U_p = 20 V, welding speed of 15 m/h (*1* — PAW; *2* — stationary-arc welding)

In the welding mode with pulse current I_p = 160 A and pause current I_{pause} = 120 A (fixed pulse time of 0.5 s) with greater pause time, weld height increases, weld width becomes somewhat smaller, and HAZ width decreases, while penetration depth practically does not change. In the case of fixation of pause time (0.5 s) and increase of pulse time, weld height decreases, and weld width increases (that is, apparently, associated with increase of penetrability/effectiveness). HAZ width changes nonlinearly, first increasing, then decreasing and increasing again.

Analysis of welding thermal cycles allowed establishing the following features: at PAW the rate of rise of metal temperature in the HAZ overheated zone is greater than in the case of stationary-arc welding; in the high-temperature region from 1350 to 1000 °C metal cooling at PAW occurs faster, and in the region

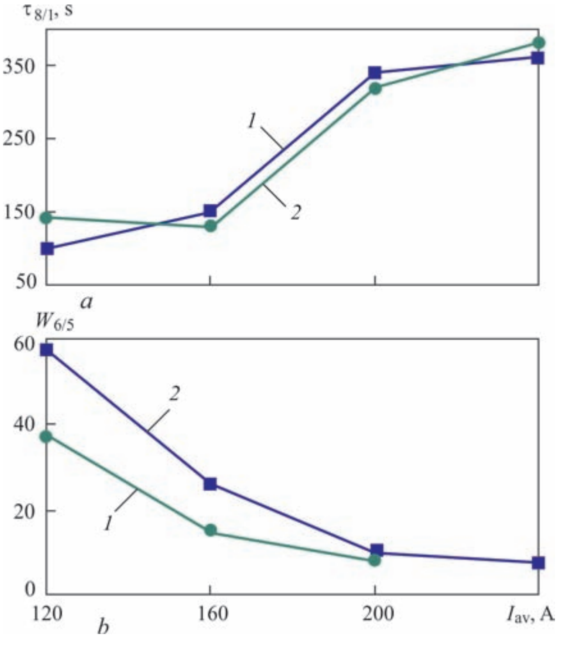

Figure 8. Change of time (*a*) and rate (*b*) of cooling of the overheated zone of HAZ metal at PAW (*1*) and stationary-arc welding (*2*) with the speed of 15 m/h. Deposition of high-alloyed welding wire HORDA 307 on 10 mm plates from 09G2S steel

of temperatures below 1000 °C it proceeds slower (Figure 7). More detailed analysis of the effect of pulsed welding mode on the rate of metal cooling in the HAZ is given in Figure 8. The given data show that the rate of metal cooling in the range of temperatures of the lowest austenite stability of 600–500 °C is lower for PAW, than in the case of stationary-arc welding, whereas time $\tau_{8/1}$ has close values.

Changes of cooling conditions, observed at transition from stationary-arc welding to PAW suggest that in this welding process a more favourable structure with a higher cold cracking and brittle fracture resistance will form in the metal of HAZ of high-strength steels with $\sigma_{0.2}$ > 600 MPa. Work in this direction will be the result of out further studies.

Conclusions

1. Pulsed-arc welding allows reducing metal spattering, HAZ width, and increasing penetration depth (practically 2 times) compared to stationary arc welding. Rate of metal cooling in the HAZ in the temperature range of 600–500 °C is here reduced practically 1.5 times.

2. Application of pulsating-arc welding allows increasing weld width and reducing HAZ width, compared to stationary-arc welding.

3. Processes of pulsed-arc welding and pulsating-arc welding feature greater capabilities for controlling the weld parameters and heat input.

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