https://doi.org/10.37434/tpwj2021.12.01

INFLUENCE OF A FORCED MODE OF PULSED-ARC WELDING ON THE STRUCTURE AND PROPERTIES OF JOINTS OF STEEL OF THE STRENGTH CLASS C440

A.V. Zavdoveev[1], **V.D. Poznyakov**[1], **M. Rogante**[2], **S.L. Zhdanov**[1],
T.G. Solomiichuk[1], **O.A. Shyshkevych**[1]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Rogante Engineering Office
62012 Civitanova Marche, Italy

ABSTRACT

In the work the influence of a pulsed-arc forced welding on the structure formation and properties of welds and HAZ metal as compared to standard pulsed-arc welding was studied. On the example of a high-strength S460M steel, it was shown that a pulsed-arc forced welding can effectively regulate the structural formation. Change in the welding thermal cycle, namely, accelerated heating and delayed cooling leads to the formation of the optimal structure in the weld and HAZ, which allows obtaining high strength and resistance to brittle fracture. Advantages of a pulsed-arc forced welding allow welding without edge preparation, which significantly improves the efficiency of the process as a whole.

KEY WORDS: pulsed-arc welding, high-strength steel, weld and HAZ metal, thermodeformation cycle, structure, properties of welded joints

INTRODUCTION

In recent years, a continuous increase in the share of welded structures made of steels with enhanced strength is observed. Quality requirements in many industries, such as shipbuilding, civil engineering, hydropower, etc., dictate new rules regarding the development of welding technologies for metal structures while maintaining a high complex of operation properties [1–5]. A simultaneous increase in both mechanical properties as well as ductility can be achieved by adding microalloying elements to steels. The released dispersion carbides and carbonitrides of microalloying elements reduce the grain size either by blocking the migration of austenite grain boundaries or by delaying its recrystallization. As a result, the carbon content can be reduced in microalloyed steels and thus their weldability can be improved, in contrast to the situation with high-strength grades of steel C–Mn.

A further increase in the yield strength of structural steels can be achieved by a special method of rolling, which includes thermomechanical treatment. This requires systematic control of both temperature as well as degree of deformation during metal formation.

Thermomechanical treatment requires fulfilment of the rolling process in such a way that individual stages of steel deformation take place at specified temperatures. Here two main effects are used:

- effect of fine-grained structure on improving mechanical properties and increase in impact strength;
- limitation or delay of recrystallization, which is achieved by introduced microalloying elements (Nb, Ti).

Thermomechanically treated steels with a high level of strength and relatively low carbon equivalent greatly simplify the solution to the problem of improving quality and reliability of metal structures. However, this raises new issues in terms of technologies for welding such steels. Namely, a carbon equivalent alone is no longer enough to study the weldability of thermomechanically treated steels. In the first turn this is predetermined by the peculiarities of the structural state of such steels, which is not taken into account by the carbon equivalent at all. Technical and economic aspects, arising from the possibility of manufacturing products from these steels and their use in energy efficient industries, as well as their suitability for the construction of different structures, including those, operating in extreme climatic conditions, are of great importance for materials science. The problems related to this group of steels require solutions in order to improve the technologies used for the manufacture of metal structures from these steels applying welding methods. One of the promising ways to solve the problems of welding thermomechanically treated steels is the use of pulsed-arc welding (PAW), which allows controlling the modes and welding thermal cycles in a wide range [6–11]. In the previous investigations, the use of PAW to thermomechanically strengthened S460M steel [12] showed the perspective of using this method. However, there is a need to further improvement of the technological process of welding thermomechanically strengthened steels, namely to reduction in the harmful effects of welding thermal cycle on the heat-affected-zone and increase

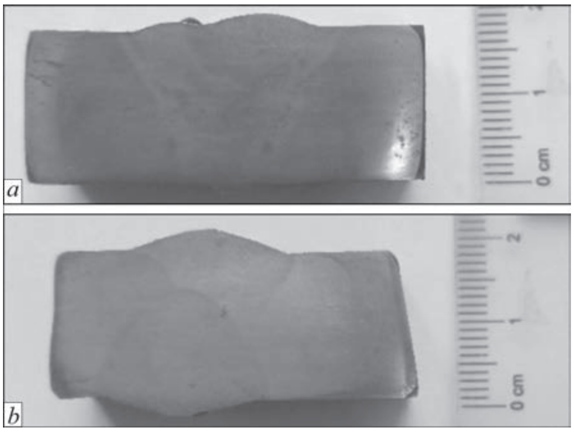

Figure 1. Macrosections of specimens of butt joints made by PAW (*a*) and PAW on a forced mode (*b*)

in the process efficiency. To solve these problems, in the presented work it is proposed to use PAW on a forced mode, which differs significantly from a standard one. Therefore, for the successful use of PAW on a forced mode in the development of modern welding technologies, the study of the influence of the modes of this welding process on the formation of the structure and properties of weld and HAZ metal as compared to stationary arc welding was carried out.

PROCEDURE OF INVESTIGATIONS

In the presented work, thermomechanically strengthened S460M steel [12] (strength class C440) was used, manufactured in accordance with DSTU EN 10025-4:2007. The chemical composition of S460M steel, wt.%: 0.15 C; 0.23 Si; 1.3 Mn; 0.09 Cr; 0.019 Ni; 0.01 V; 0.05 Nb; 0.025 Al; 0.013 S and 0.017 P.

As a power source, the rectifier of inverter type ewm Phoenix Pulse 401 (of MULTIMATRIX Company) was used, which provides different pulse frequency at PAW [12]. To determine the welding and technological characteristics of the current source, a digital oscilloscope UTD2000CEX-II was used, which allows recording the volt-ampere characteristics of the power source in a wide range. To record oscillograms, a shunt 75ShSM with a resistance of 150 μOhm was used. This allowed recording welding currents of up to 500 A, while the voltage drop on the shunt was 75 mV.

Figure 2. Equipment for record of welding thermal cycles

For the basic comparative specimen, as in the previous studies [12], welding in shielding gases (Ar + 18 % CO_2) of S460M steel joints of 16 mm thickness with a V-shaped edge preparation by a solid cross-section wire G3Sil of 1.2 mm diameter was used (Figure 1, *a*). Root passes during welding of this steel were produced on a copper substrate. The mode of automated PAW was as follows: I_m = 220–240 A, U_a = = 26–28 V, v_w = 14.21 m/h. In this case, where I_{pls} is the current in the pulse (450 A), I_p is the current in the pause (160 A), t_{pls} and t_p are the duration of the pulse and the pause, respectively. Test specimens using PAW on a forced mode were produced for butt joints without edge preparation: I_m = 320 A, U_a = 28 V, v_w = = 8 m/h. It should be noted that in this case a high quality weld formation with a full penetration was provided (Figure 1, *b*), which is impossible in the case of using a traditional welding process.

To study the effect of PAW modes on welding thermal cycles, appropriate experiments were performed. To record WTC, steel plates with a thickness of 10 mm (Figure 2) were used, in which chromel-alumel thermocouples were drilled-in to a depth of 7.5–8.0 mm. This value of the drilling depth is based on the previous studies and is predetermined by the need in recording WTC in the HAZ region.

Metallographic examinations were performed using a scanning electron microscope Mira 3 LMU (Tescan). During the study, the secondary electron detector (designation SE on the electronic image) and the elastically reflected electron detector (designation BSE on the electron image) were used. To evaluate the elemental composition during the study, the detector-spectrometer Oxford X-Max 80 and the analytical software product INCA Energy[*] were used.

The microhardness of the individual structural components and the integral hardness of the metal were measured in a hardness tester M-400 of the LECO Company at a load of 100 g (*HV*). The specimens for metallographic examinations were prepared according to standard procedures using diamond pastes of a different dispersion, detection of microstructure was performed by chemical etching in a 4 % alcoholic solution of nitric acid.

For mechanical tests of weld and HAZ metal, the standard specimens were manufactured from welded joints. The specimens for static (short-term) tensile tests corresponded to the type II in accordance with GOST 6996–96. According to the results of the carried out tests, the effect of the welding method on the change

---

[*] The authors express gratitude to V.A. Kostin for his promotion in conducting metallographic examinations.

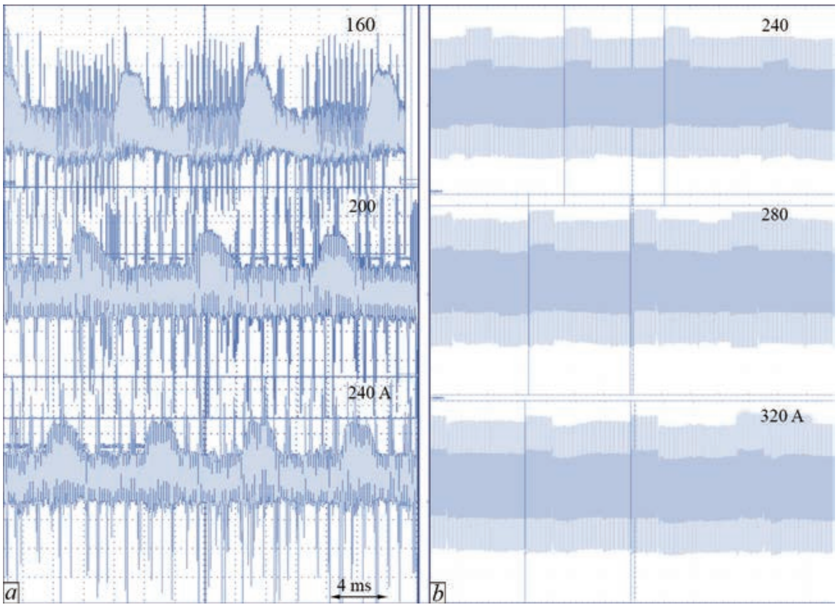

Figure 3. Oscillograms for inverter power source, standard pulsed-arc (*a*) and pulsed-arc forced mode (*b*) of welding

of the following indices of HAZ metal was evaluated: strength (σ_y and σ_t, MPa), ductility (δ_5 i ψ, %).

The ability of the metal to resist brittle fracture was determined using the approaches from fracture mechanics. The values of the criteria K_{1C} and δ_c were determined by standard procedures and formulas given in [12]. To determine the values of the critical stress intensity factor K_{1C} and critical opening of the crack δ_c, the specimens of a rectangular cross-section 10×20×90 mm with a notch length of 7 mm and a fatigue crack with a length of 3 mm were used. These specimens were tested for three-point bending in the temperature range from 20 to –40 °C.

RESULTS AND THEIR DISCUSSION

INVESTIGATION OF WELDING AND TECHNOLOGICAL CHARACTERISTICS OF PAW

In addition to the normal welding mode, the ewm Phoenix Pulse 501 has a forced PAW mode. Features of this mode were studied, starting from oscillograms of change of welding current depending on time. Figure 3 shows oscillograms for PAW of standard and forced modes. Detailed analysis showed that the pulse repetition frequency corresponds to 58 kHz, and it corresponds to the standard PAW. The forced mode differs in the duty cycle of pulses. If in the standard pulsed-arc mode with a growth in the mean welding current the duty cycle increases, then in the forced mode the duty cycle is unchanged, instead, the parameters of the currents in the pulse and in the pause change. In the pulse the current is constant and equal to 500 A, and the pause current grows with an increase in the mean current. In addition, the shape of the pulse differs significantly, namely, if in PAW on the standard pulsed-arc mode the pulse has a parabolic shape, as was established in [12], then in the case of a forced mode, the shape of the pulse is rectangular. And the effective welding current is equal to the mean welding current, while during PAW in the standard mode, the effective welding current is by 25 % higher (Figure 4).

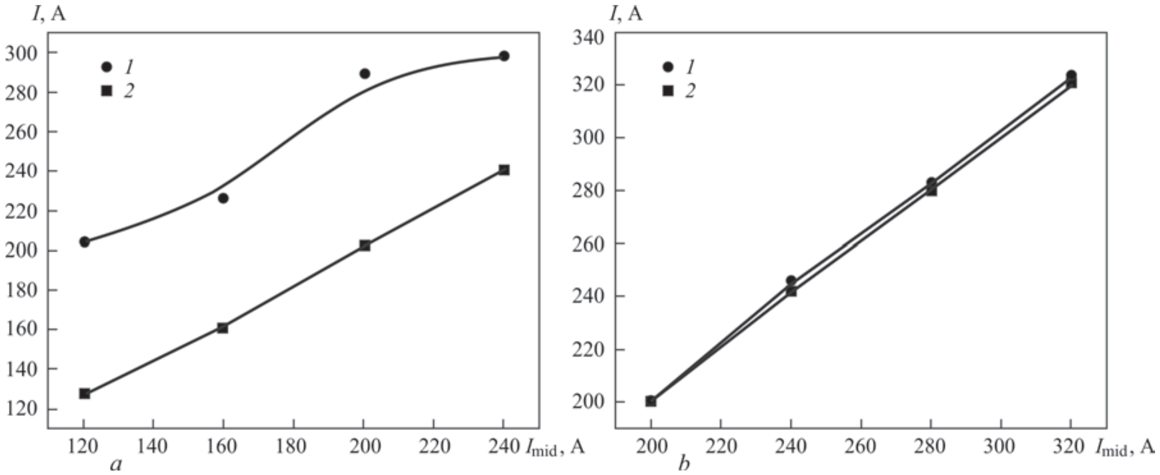

Figure 4. Dependence of effective (*1*) and mean (*2*) welding currents, standard pulsed-arc (*a*) and pulsed-arc forced mode (*b*) of welding

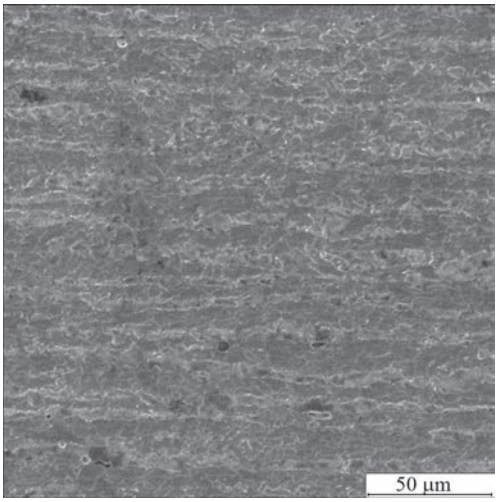

Figure 5. Microstructure of S460M steel

INVESTIGATION OF THE STRUCTURE AND PROPERTIES OF THE BASE METAL

As a result of performing a controlled thermomechanical rolling in the temperature range of 900–700 °C with an accelerated cooling in the initial structure of S460M steel, a fine-grained banded ferrite-pearlite structure with a grain size of about 20 μm and hardness *HV* 195 is formed (Figure 5).

This structure of S460M steel of the abovementioned chemical composition provides the following level of mechanical properties: yield strength $\sigma_{0.2}$ = = 452 MPa, tensile strength σ_t = 581 MPa, elongation δ_5 = 26 %, reduction in area ψ = 58 %.

Metallographic examinations of the structure (Figure 6) of welded joints of S460M steel, which were performed in the previous work [12], show that in PAW, the microstructure of the weld metal consists of refined plates of acicular ferrite (1–3 μm) and a reduced amount of polyhedral ferrite (5–10 %) and precipitates of polygonal ferrite (3–10 μm), located along the boundaries of primary austenitic grains. Such changes in the microstructure lead to an increase in hardness in the weld to 2420 MPa as compared to the base metal. In the region of a coarse HAZ grain, a bainite structure with a negligible share (up to 3–5 %) of martensite is observed. The hardness of this region of HAZ increases accordingly to 3250–3340 MPa. The structure of the HAZ region of a refined grain consists of a mixture of upper and lower bainite (2650–2810 MPa). In the region of a partial HAZ recrystallization, pearlite and ferrite are observed, which significantly reduces the Vickers hardness of metal to 2320–2400 MPa.

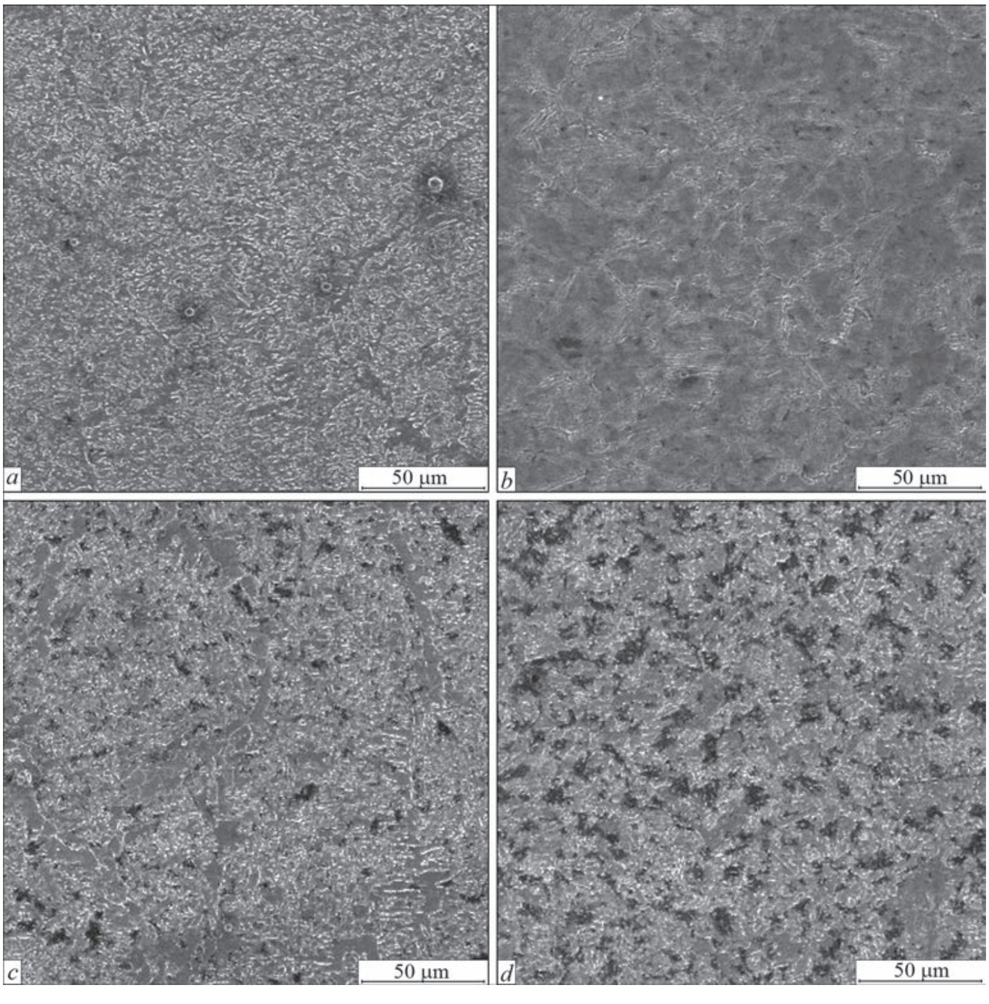

Figure 6. Microstructure of weld (*a*, *c*) and HAZ metal (*b*, *d*) of S460M steel, made by pulsed-arc (*a*, *b*) and pulsed-arc forced (*c*, *d*) welding

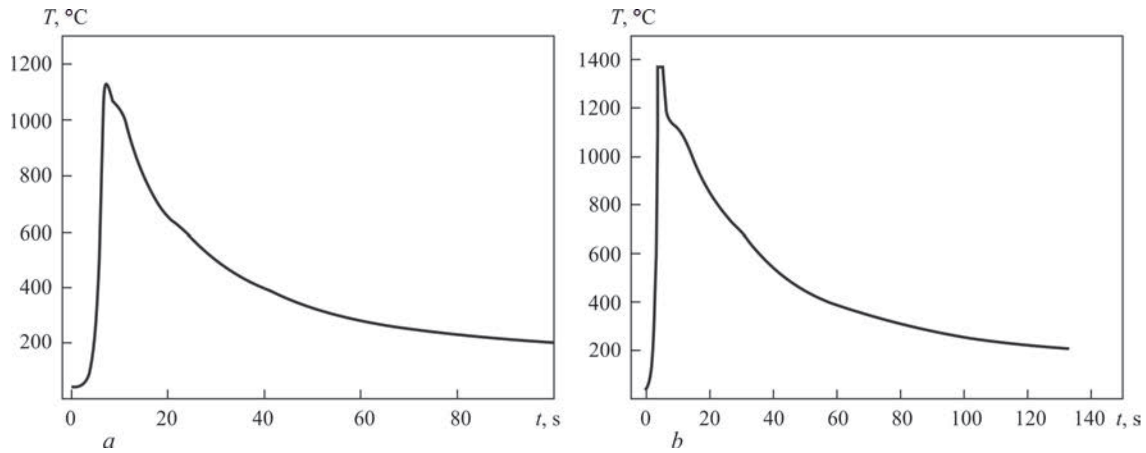

Figure 7. Welding thermal cycles for PAW (*a*) and PAW on a forced mode (*b*)

In PAW on a forced mode, the microstructure of the weld metal differs significantly from the microstructure of the weld metal produced by a standard PAW, namely: acicular ferrite with some larger plates is observed, and precipitates of polygonal ferrite became wider and their specific share increased. As a result, in the metal a decrease in microhardness to 2050 MPa occurs. In the region of a coarse HAZ grain, mainly acicular ferrite with an ordered second phase is observed. The hardness in this region of HAZ, respectively, is equal to 2400–2480 MPa. In the region of a partial recrystallization of HAZ, the formation of pearlite and ferrite is observed, which significantly reduces its hardness to 2160 MPa.

Such differences in the microstructure are predetermined by the peculiarities of WTC running in PAW (Figure 7). Due to the fact that in PAW the temperature of the metal is above 1000 °C, the cooling rate will be much higher, which leads to the formation of a martensitic component in the structure. In PAW the temperature of metal is below 1000 °C, the cooling rate of HAZ metal is lower than that of arc welding, which contributes to the diffusion processes during structural transformations.

In pulsed-arc welding processes, as is noted by the author of [11], WTC plays a key role during hardening of weld metal, as it affects the refinement of structural components by influencing crystallization processes in the welding pool.

The study of hardness (Figure 8) of welded joints revealed that at a forced PAW, its level in the weld metal is lower than 15 % of the hardness of the weld metal produced by a standard PAW. This is predetermined by the peculiarities of the structure formation. In HAZ metal, the hardness values in a pulsed-arc forced welding are also lower than in a standard PAW. This fact is an additional advantage of a forced PAW, as far as in the welded joint a uniform distribution of mechanical properties will be formed. It should be noted that at a forced PAW, the hardness in HAZ decreases to the level of the source metal more slowly.

From the data given in the Table 1 it is seen that under PAW conditions, higher values of strength of the weld metal are achieved as compared to the base metal. Ductility remains at a fairly high level. The values of strength of the weld metal are in a good agreement with the hardness in the weld metal region, namely, they do not exceed the values of the base metal by more than 20 %. When using forced PAW, taking into account that the values of hardness of HAZ metal are not more than 20–25 % from the base metal, it provides the equal strength of the welded joint.

To evaluate the sensitivity of metal regions in welded joints to the concentration of stresses in the conditions of plane deformation under static load, the force criterion is used, which is the critical stress intensity factor K_{1C}. When increasing the values of K_{1C}, the sensitivity of metal to stress concentration decreases. Deformation criteria of fracture are used to determine the crack resistance of fracture materials, which is accompanied by significant plastic deformations in the region near the tip of the crack and precedes its propagation. This criterion is called critical opening of the crack tip δ_c. If the opening of the edges is greater than δ_c, than adhesion stresses are equal to zero. It is used to evaluate the resistance of metal to brittle fracture

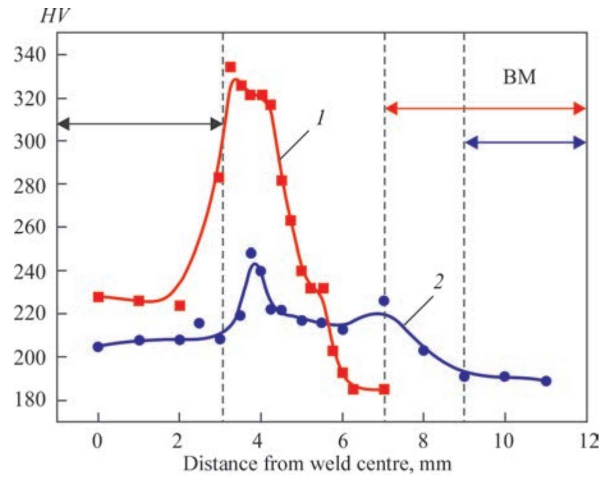

Figure 8. Hardness of welded joints of S460M steel in PAW (*1*) and PAW on a forced mode (*2*)

Table 1. Mechanical properties of weld metal of joints of S460M steel in different welding methods

Region	Welding method	σ_y, MPa	σ_t, MPa	δ	ψ
Weld	PAW	570	667	24	68
	PAW on a forced mode	590	675	23	55
BM		452	581	26	60

under the conditions of a large plastic deformation, when the crack at its tip reaches a critical sizes of the value δ_c and begins to propagate rapidly, using the energy released during its further growth. The indices of resistance of HAZ metal of welded joints produced by a standard (K_{1C} = 100 MPa√m, δ_c = 0.11 mm) and a forced (K_{1C} = 100 MPa√m, δ_c = 0.18 mm) PAW to brittle fracture, almost equal and are at a sufficiently high level, which is predetermined by the peculiarities of the structure formation.

CONCLUSIONS

Studies of the effect of standard and forced PAW on the structure and mechanical properties of thermomechanically treated S460M steel allowed finding the following advantages of the latter:

- as compared to the standard PAW, the forced one allows performing welding without edge preparation with producing a high-quality welded joint;
- 30 % lower values of microhardness in the heat-affected-zone of the welded joint as compared to the standard PAW is predetermined by the peculiarities of the welding thermal cycle;
- 15 % lower values of microhardness of weld metal as compared to the standard PAW and close to the values of the base metal, which is provided by the formation of a favourable microstructure;
- high level of resistance to brittle fracture of welded joints.

The mentioned features of a forced pulsed-arc welding allow providing high mechanical properties of welded joints of thermomechanically strengthened S460M steel, which is the main problem for this class of steel. It was demonstrated that the ability to perform forced PAW without edge preparation, in addition, can improve the process efficiency by 40 %.

REFERENCES

1. Lee, C.H., Shin, H.S., Park, K.T. (2012) Evaluation of high strength TMCP steel weld for use in cold regions. *J. Constr. Steel Res.*, **74**, 134–139. DOI: https://doi.org/10.1016/j.jcsr.2012.02.012.
2. Medina, S.F., Gómez, M., Gómez, P.P. (2010) Effects of V and Nb on static recrystallisation of austenite and precipitate size in microalloyed steels. *J. Mater. Sci.*, **45**, 5553–5557. DOI: https://doi.org/10.1007/s10853-010-4616-z.
3. Fossaert, C., Rees, G., Maurickx, T., Bhadeshia, H.K.D.H. (1995) The effect of niobium on the hardenability of microalloyed austenite. *Metall. Mater. Transact. A*,. **26**, 21–30. DOI: https://doi.org/10.1007/BF02669791.
4. Nazarov, A.V., Yakushev, E.V., Shabalov, I.P. et al. (2014) Comparison of weldability of high-strength pipe steels microalloyed with niobium, niobium and vanadium. *Metallurgist*, **7**, 911–917. DOI: https://doi.org/10.1007/s11015-014-9821-6.
5. Zavdoveev, A., Poznyakov, V., Baudin, T. et al. (2021) Welding thermal cycle impact on the microstructure and mechanical properties of thermo-mechanical control process steels. *Steel Research Int.*, 92(**6**), 2000645.
6. Needham, J.C., Carter, A.W. (1965) Material transfer characteristics with pulsed current. *Brit. Weld. J.*, **5**, 229–241.
7. Palani, P.K., Murugan, N. (2006) Selection of parameters of pulsed current gas metal arc welding. *J. of Materials Proc. Technology*, **172**, 1–10.
8. Tong, H., Ueyama, T. et al. (2001) Quality and productivity improvement in aluminium alloy thin sheet welding using alternating current pulsed metal inert gas welding system. *Sci. Technol. Weld. Join.*, 6(**4**), 203–208.
9. Poznyakov, V.D., Zavdoveev, A.V., Gajvoronsky, A.A. et al. (2018) Effect of pulsed-arc welding modes on the parameters of welded joints produced with Sv-08Kh20N9G7T wire. *The Paton Welding J.*, **9**, 7–12.
10. Amin, M., Ahmed, N. (1987) Synergic control in MIG welding 2-power current controllers for steady dc open arc operation. *Met. Construct.*, **6**, 331–340.
11. Rajasekaran, S. (1999) Weld bead characteristics in pulsed GMA welding of Al–Mg alloys. *Weld. J.*, 78 (**12**), 397–407.
12. Zavdoveev, A.V., Poznyakov, V.D., Rogante, M. et al. (2020) Features of structure formation and properties of joints of S460M steel made by pulsed-arc welding. *The Paton Welding J.*, **6**, 9-13. DOI: https://doi.org/10.37434/tpwj2020.06.02

ORCID

A.V. Zavdoveev: 0000-0003-2811-0765,
V.D. Poznyakov: 0000-0001-8581-3526,
M. Rogante: 0000-0002-6846-0826

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.D. Poznyakov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
E-mail: paton39@ukr.net

SUGGESTED CITATION

A.V. Zavdoveev, V.D. Poznyakov, M. Rogante, S.L. Zhdanov, T.G. Solomiichuk, O.A. Shyshkevych (2021) Influence of a forced mode of pulsed-arc welding on the structure and properties of joints of steel of the strength class C440. *The Paton Welding J.*, **12**, 3–8.

JOURNAL HOME PAGE

https://pwj.com.ua/en

Received 30.06.2021
Accepted: 24.12.2021