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STRUCTURE AND PROPERTIES OF WELDED JOINTS OF 13KhGMRB STEEL IN PULSED-ARC WELDING

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ABSTRACT

The results of studies on the structure formation in the welds and heat-affected-zone (HAZ) metal of low-alloy heat-strengthened 13KhGMRB steel in a pulsed-arc welding, changes in mechanical properties and stress intensity factor in brittle fracture and resistance to cold and fatigue cracks formation are given. It was found that compared to stationary arc welding, in a pulsed-arc welding in the structure of welds and HAZ metal of joints, a larger number of hardening structures of bainite and martensite is formed. It was determined that regardless of the welding method, the values of strength ($\sigma_{0.2}$ and σ_t) and ductility (δ_5 and ψ) of metals are approximately at the same level while their ability to resist impact loads, especially at a test temperature –40 °C, in the case of pulsed-arc welding grows. In particular, it was determined that the values of impact toughness of the HAZ metal of welded joints produced using pulsed-arc welding are by 30 % higher compared to arc welding and amount to 108 J/cm^2. I.e., the cold resistance of the weld metal is clearly increased. The resistance of weld and HAZ metals to brittle fracture is at a fairly high level ($Kq \geq 84$ MPa$\sqrt{\text{m}}$). It was also established that due to an increase in hardening structures in the HAZ metal of the welded joints produced using pulsed welding, the temperature of preliminary heating should be increased from 90 to 120 °C to avoid the cold cracks formation. Instead, such welded joints have a higher resistance to fatigue cracks formation at cyclic bending load.

KEYWORDS: low-alloy heat-strengthened steel, pulsed-arc welding, weld metal, HAZ, structure, mechanical properties, cold cracks, brittle fracture, fatigue resistance

INTRODUCTION

In the manufacture of critical metal structures in various industries, such as civil construction, mechanical engineering, bridge building, etc., low-alloy heat-strengthened C690 steels with $\sigma_{0.2}$ = = 580–750 MPa are increasingly used. This allows a significant increase in the load on construction facilities and extends their service life. The safe operation of such structures is largely determined by the quality of welded joints production, which should meet the requirements of equal strength, cold resistance and have a sufficiently high resistance to brittle and fatigue fracture. It should also be noted that difficulties in welding low-alloy high-strength steels with $\sigma_{0.2}$ = = 580–750 MPa are associated with the need in preventing the probability of cold cracks formation in the weld and HAZ metals, determined by the formation of hardening structures [1, 2]. The solution of these problems is complicated by the condition that welded joints should have the required values of service and technological properties after welding without additional heat treatment. This is especially important when welding heat-strengthened steels, the structure and properties of whose welded joints are significantly influenced by heating and cooling parameters typical for arc welding. A typical representative of this steel grades is a low-alloy heat-strengthened 13KhGMRB steel. Namely regarding the joints of this steel, which was welded using traditional arc processes, the technical literature provides a sufficient information on the influence of technological modes of welding on the structure, mechanical properties and ability of welded joints to resist the cold cracks formation.

It should be noted that recently, in the world practice, in the manufacture of welded structures, pulsed-arc welding processes are increasingly used. Pulsed-arc welding (PAW) is characterized by a periodically changed arc power [3, 4–8], which allows solving the complex technological problems in the manufacture of unique structures and improving the efficiency of welding processes. PAW provides expanded abilities to control the processes of melting and electrode metal transfer, stirring of molten metal, and also it becomes possible to regulate the properties and sizes of the weld and HAZ metal of welded joints. This improves the formation of joints when producing them in different spatial positions while providing smooth transitions from the weld to base metal [9–16]. At the same time, in the technical literature there is no sufficient information on the influence of the features of pulsed-arc welding process on the structure formation, mechanical properties of welded joints from high-strength steels prone to hardening and their ability to resist the cold cracks formation.

In view of this, the aim of the work was to obtain the comparative test results in determination of the effect of welding method, namely PAW, on the structure of welds and HAZ metals of welded joints of low-alloy heat-strengthened 13KhGMRB steel, change of mechanical properties, on the resistance of joints to cold and fatigue cracks formation, that has a certain scientific and practical importance.

RESEARCH PROCEDURE

The aim of research was welded joints of high-strength low-alloy 13hGMRB steel of the following chemical composition, %: 0.13 C; 0.31 Si; 1.71 Mn; 0.96 Cr; 0.45 Mo; 0.03 Ni; 0.046 Nb; 0.002 B, 0.01 S and 0.015 P, which were produced in mechanized welding using a stationary arc (base option), in welding on a pulsating mode by modulated current (for comparison) and in PAW (process under study).

As the power source, inverter rectifier EWM Phoenix Pulse 500 was used, which provides a different frequency of pulses in pulsed-arc welding. Mechanized welding in a mixture of shielding gases (82 % Ar + 18 % CO_2) of joints of 13KhGMRB steel of 20 mm thickness with a V-shaped edge preparation was performed using a solid cross-section wire Sv-10KhN2GSMFTYu with a diameter of 1.2 mm. Welding using a conventional process with a stationary arc was performed on such mode: I_w = 180–200 A, U_a = 26 V, V_w = 15–18 m/h. Welding mode by pulsating arc: pulse current I_A = 220 A, pause current I_B = 80 % from I_A, U_a = 26–27 V, duty cycle 0.5, frequency 1.33 Hz. In PAW, the mode was the following: I_{av} = 220–240 A, U_a = 26–28 V, V_w = 14–21 m/h (pulsed current I_{max} = 450 A, pause current I_{min} = 120–165 A, duty cycle 0.33–0.36, frequency 120–150 Hz) [17, 18].

Metallographic examinations were performed using a light microscope Neophot-32 and a scanning electron microscope Mira 3 LMU (Tescan). In the examination, the detector of secondary electrons (SE designation on the electron image) and the detector of back-scattered electrons (BSE designation) were used. The microhardness of individual structural components and the integral hardness of the metal were measured in the durometer M-400 of the LECO Company at a load of 100 g (*HV*). The specimens for metallographic examinations were prepared by standard procedures with the use of diamond pastes of different dispersion, the microstructure was revealed by chemical etching in a 4% alcohol nitric acid solution.

To test the mechanical properties of the weld and HAZ metals of welded joints, standard specimens were manufactured for the tests on static tension and impact bending (specimens respectively of type II and IX of GOST 6996–96)*. According to the results of the carried out tests, the influence of the welding method on the change in the values of strength (σ_y and σ_t), ductility (δ_5 and ψ) and impact toughness (*KCV*) were evaluated.

The ability of the metal to resist brittle fracture was determined using the fracture mechanics approaches, according to which the specimens of 10 mm thickness with an indicated fatigue crack at the apex of the notch were used, preliminary cut from the welded joints. Then, at a static bending load, the critical stress intensity factor *Kq* was determined. To determine the values of the critical stress intensity factor, the procedure was used according to [13]. At the same time, the dependence established earlier was taken into account, that when *Kq* values grow, the sensitivity to the stress concentration decreases and the resistance of the metal to brittle fracture rises, or vice versa, with a decrease in the factor, the resistance decreases.

The resistance to cold cracks formation was evaluated with the help of a butt technological Tekken specimen. As a test criterion, the preheating temperature was taken, in which cracks in the weld or HAZ metal of welded joints were not formed.

The fatigue tests were performed on the specimens of T-welded joints of 12 mm thickness at their cyclic bending load. The welded joints were loaded at 14 Hz frequency at symmetric cycle stresses with a level of 30, 35 and 35 MPa. The UMP-1 machine was used for the tests. During the tests, a number of cycles, at which the formation of a fatigue crack of a critical length (3 mm) and a stress, at which the specimen remained undamaged after $2.1\cdot10^6$ load cycles were registered.

RESULTS OF WORK AND THEIR DISCUSSION

According to the results of studying mechanical properties, it was determined that the values of static strength of welded joints, produced with the use of the abovementioned arc welding processes are almost comparable (Figure 1, *a*). Namely, the yield strength of welds metal of the welded joints is in the range of $\sigma_{0.2}$ = 713–740 MPa. The lower values are typical of the stationary process, and the higher values are inherent in PAW. The same tendency is observed for the values of ultimate rupture strength of the welds metal — σ_t = 786–800 MPa. For the abovementioned welding methods, the values of ductility (Figure 1, *b*) also does not differ significantly. Thus, the values of relative elongation of the welds metal of the welded joints are within δ_5 = 16–19 %, and those of reduction in area are ψ = 59–67 %. Unlike the values of strength and ductility, the effect of welding process on the value of impact toughness of both the welds and

HAZ metal of welded joints is more significant and ambiguous (Figure 2).

As for the values of impact toughness of the welds metal, at the test temperature of 20 °C, the highest values of KCV_{+20} = 133 J/cm^2 are typical for the stationary process. In welding using pulsating arc and in PAW, they are reduced relatively to 117 and 96 J/cm^2. The same tendency to reduce *KCV* values of the weld metal is maintained in the case of testing specimens at –20 °C. In this case, the values of impact toughness of the welds metal of welded joints made accordingly by an arc that burns stationary, using pulsating arc and using PAW are 79, 69 and 62 J/cm^2. Instead, in the case when the specimens were tested at a temperature of minus 40 °C, significant differences between *KCV* values of the welds metal of studied welded joints are not observed. They are almost identical and are in the range of 43–49 J/cm^2. It should be noted that despite the reduction in impact toughness typical of pulsed welding processes, they remain at a high level and meet the requirements of standard documents for impact toughness of 13KhGMRB steel ($KCV_{40} \geq 39$ J/cm^2).

Some other regularities for changing impact toughness are peculiar to the HAZ metal of welded joints (Figure 2). The same as in the study of the specimens with a notch over the weld metal, the highest values at a test temperature of 20 °C, which are equal to 150 J/cm^2, are typical of a stationary welding process. For the pulsating arc and for PAW these values are 97 and 113 J/cm^2. At a test temperature of –20 °C, the tendency of reduction in the values of cold resistance begins to change. The difference between *KCV* values is significantly reduced and they are respectively 113, 94 and 108 J/cm^2. At the test temperature of –40 °C, the difference between the values of impact toughness of the HAZ metal of welded joints made using a stationary welding process and welding using pulsating arc almost was not observed. These welding processes are characterized by the values of impact toughness in the range from 73 to 79 J/cm^2. They are much higher and, moreover, those at the level of values of impact toughness of the specimens that were tested at a temperature of –20 °C (KCV_{-40} = 108 J/cm^2), characteristic of the HAZ metal of the welded joints made using PAW. I.e., the cold resistance of the HAZ metal of the joints made using PAW clearly increases.

Concerning the results of studying the specimens, the test of which was performed using the force criterion of fracture mechanics, no significant differences in the values of *Kq* were detected. In all cases, the resistance of the welds and HAZ metals of welded joints to the brittle fracture is at a high level (Figure 3). It was determined that the metal of welds of

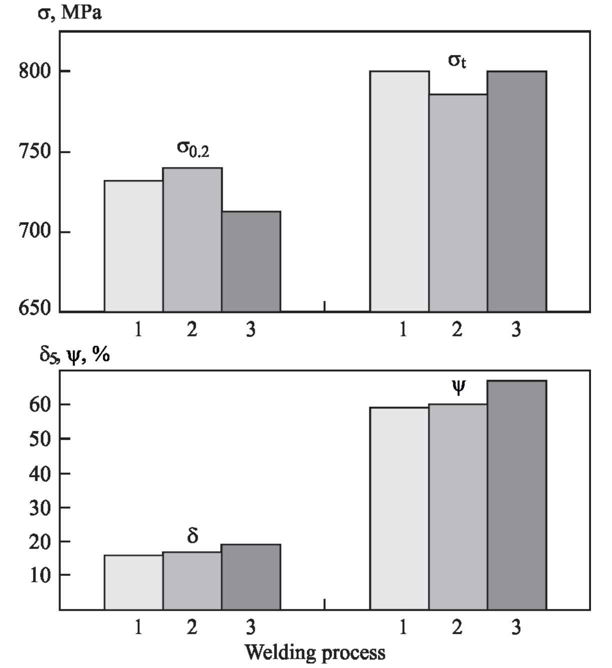

Figure 1. Mechanical properties of welds metal of welded joints of 13KhGMRB steel: *1* — pulsating arc; *2* — PAW; *3* — stationary arc

the welded joints of 13KhGMRB steel, made both by PAW as well as welding with a pulsating arc in the studied temperature range has approximately the same values of *Kq*. At a test temperature of 20 °C, it amounts to 94.6–95.6, at –20 °C –88–89.1, and at –40 °C 84.7–85.8 MPa√m (Figure 3, *a*, *c*). Also, a significantly high resistance to brittle fracture belongs to the HAZ metal, namely the stress intensity factor, depending on the test temperature changes in the range of 84.2–92.7 MPa√m. It should also be noted that compared to welding using stationary arc, the values of resistance almost did not change.

The mentioned differences, especially in the values of impact toughness at a low temperature, depending on the welding method are associated with changes in the phase-structural composition of the metal. The structure of 13KhGMRB steel represents a structure of tempered bainite, mostly lower, with the hardness of 253–264 *HV* (Figure 4). The structure of the upper

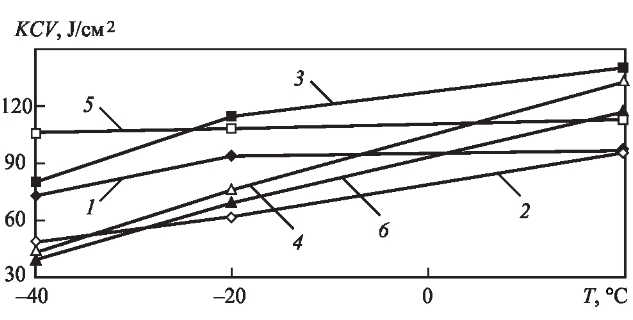

Figure 2. Impact toughness of welds and HAZ metal of welded joints of 13KhGMRB steel at different test temperatures *T*: ■ — HAZ, ▲ — weld; *1*, *2* — stationary arc; *3*, *4* — pulsating arc; *5*, *6* — PAW

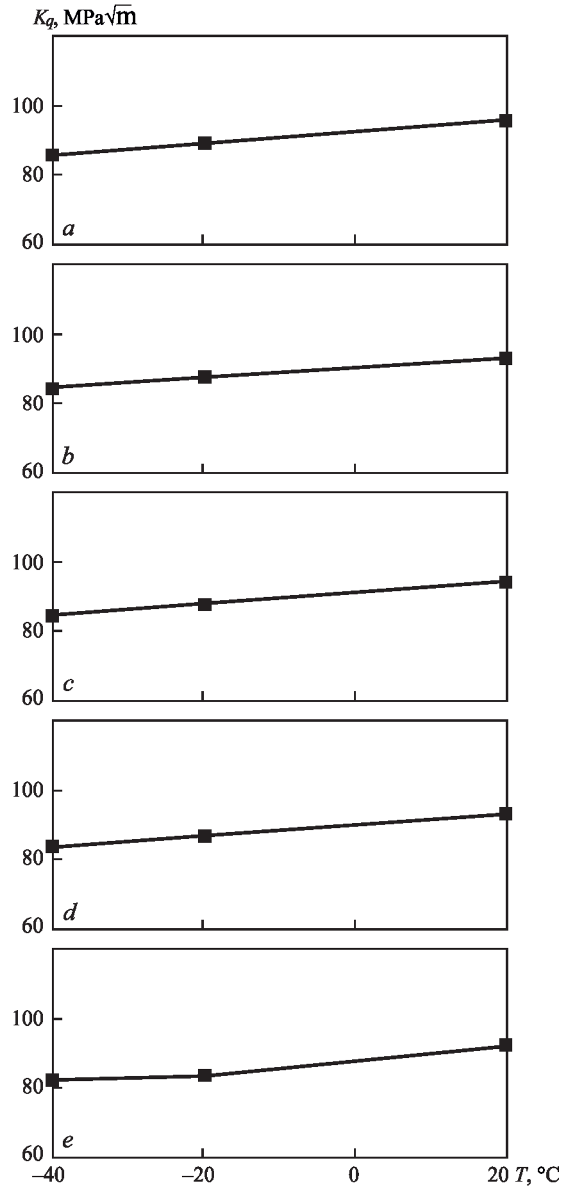

Figure 3. Resistance to brittle fracture of welds (*a*, *c*) and HAZ metal (*b*, *d*) of welded joints of 13KhGMRB steel in PAW (*a*, *b*) and pulsed-arc welding (*c*, *d*) and stationary arc (*e*)

weld layer in welding with a stationary arc consists mainly of fine-grained sorbite (Figure 5, *a*, *b*) with narrow thin precipitates of hypoeutectoid ferrite within cast crystals. The hardness of sorbite amounts to 274 *HV*. In the region of the coarse HAZ grain, a mixture of the upper and lower bainite with a hardness of 383 *HV* is observed. In the region of fine grain and in the region of partial recrystallization, a refinement of grain and a drop in hardness from 309 to 236–253 *HV* are observed.

In PAW, the structure of the upper weld layer consists of a mixture of upper and mostly lower bainite (Figure 5, *c*, *d*). The hardness of such a structure is within 317–336 *HV*. On the boundaries of cast crystallites, like in the stationary process, very thin precipitates of hypoeutectoid ferrite are observed. In the region of coarse HAZ grain, a martensitic structure with the hardness of 446–488 *HV* is observed. In the region of small grain and the region of partial recrystallization of HAZ, the sizes of grains become smaller and the hardness is reduced to 285 *HV*.

The structure of the upper layer of the specimen weld, produced by the pulsating arc, consists of a mixture of upper and lower bainite with a hardness from 262 to 314 *HV* (Figure 5, *e*, *f*). In the regions of cast crystallites, as in the previous cases, fine precipitates of hypoeutectoid ferrite are visible. In the region of coarse grain in HAZ, mainly a mixture of the upper and lower bainite with a hardness of up to 383 *HV* and small regions of martensite (401 *HV*) are observed. In the regions of small grain and partial recrystallization in HAZ, a refinement of grain and a drop in hardness to 366 *HV* is observed.

Thus, it was established, that despite the change in the welding process from stationary to pulsating and PAW, some changes occur in the formation of structures in the welds and HAZ metal of welded joints. Unlike the welds metal of welded joints made using an arc, which burns stationary and in which mostly the structure of sorbite is formed, in the metal of welds, joints made by welding with a pulsating arc and PAW, the upper and lower bainite is formed. Also changes in the structure of the welded joints HAZ metal oc-

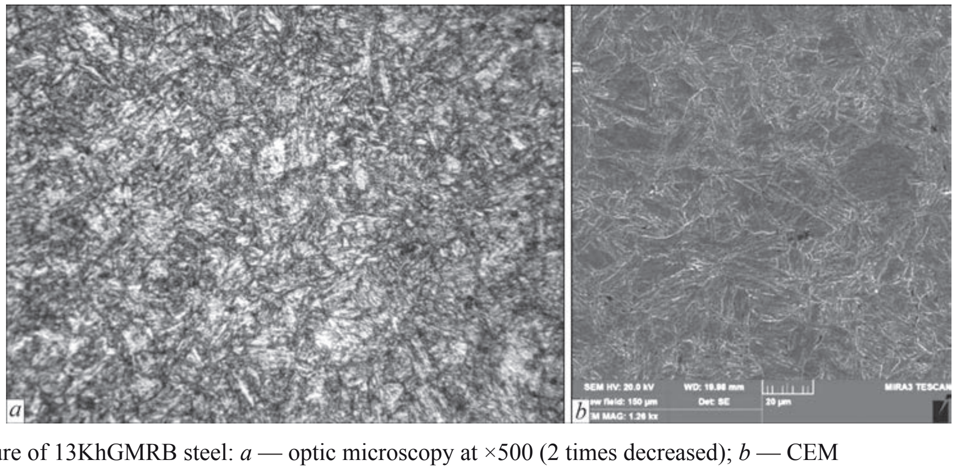

Figure 4. Structure of 13KhGMRB steel: *a* — optic microscopy at ×500 (2 times decreased); *b* — CEM

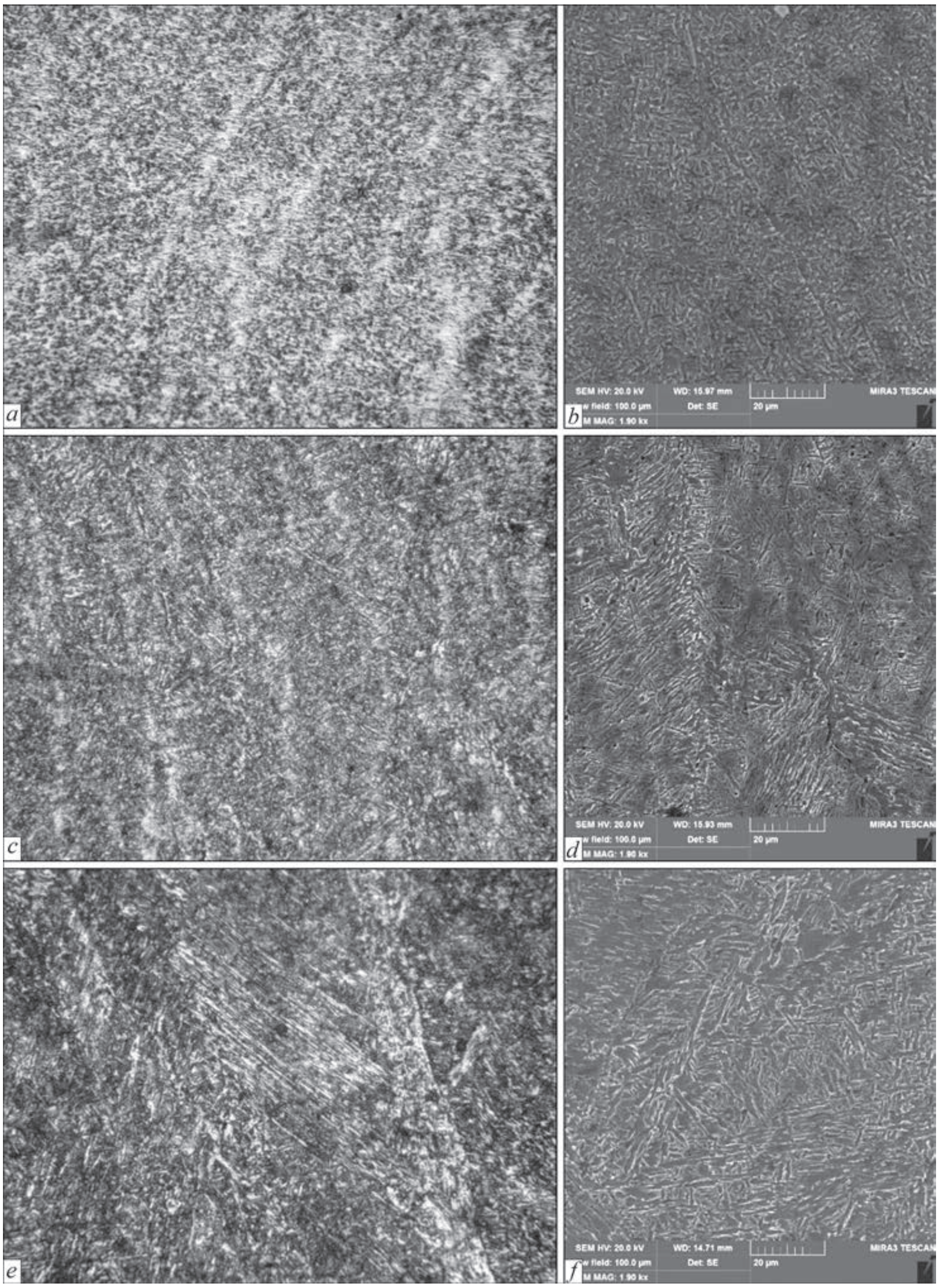

Figure 5. Structure of the upper weld layer in welding using stationary arc (*a*, *b*), in PAW (*c*, *d*) and pulsating arc (*e*, *f*): *a, c, e* — optic microscopy at ×500 (2 times decreased); *b*, *d*, *f* — CEM

cured. It was determined that unlike the HAZ metal of welded joints made using an arc that burns stationary and in which a bainite structure was formed, in a pulsed process of welding in the HAZ metal, small regions containing martensite are observed, in PAW in the region of HAZ overheating, only a martensitic structure of increased hardness is formed. Obviously, namely this predetermined the fact that in order to prevent the cold cracks formation in welded joints of 13KhGRMS steel, it is necessary to increase the temperature of their preheating. This is evidenced by the results of the abovementioned studies, the generalized

Table 1. Presence of cold cracks (CC) and depth of their propagation in the cross-section of joints (%) in PAW of low-alloy heat-strengthened steels

Steel grade	Welding method	Preliminary heating temperature T_p, °C			
		20	60	90	120
13KhGMRB	Stationary	CC (100 %)	CC (50 %)	Absent	–
	PAW	CC (100 %)	–	CC (up to 30 %)	Absent

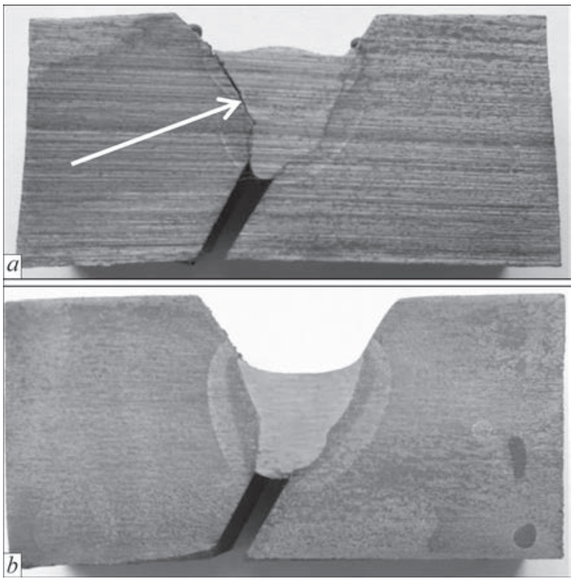

Figure 6. Macrosections of Tekken specimens of welded joints of 13KhGMRB steel, produced by PAW: *a* — without preliminary preheating; *b* — T_p = 120 °C

results of which are presented in Table 1 and typical macrosections from the Tekken specimens are given in Figure 6.

As is seen from the abovementioned material, in conventional welding using an arc that burns sta-tion-ary, the temperature of the preliminary heating (TP) of the Tekken specimens, which allows preventing the cold cracks formation in them, should be not lower than 90 °C. Regarding the Tekken specimens, the welding of which was performed by PAW, such a result can be achieved by increasing the temperature of the preliminary heating of the specimens to 120 °C (Figure 6, *b*, *c*).

Taking into account the results of the abovementioned studies, further in welding of T-joint specimens of 13KhGMRB steel, from which the specimens for testing on cyclic life were manufactured, preliminary heating of welded joints to a temperature of 120 °C was used, which was maintained at the expense of self preheating. The welding-on of the stiffeners to the steel plates was performed with a complete penetration and a leg of 12 mm. The generalized test results are shown in Figure 7.

It was determined that under the test conditions at a cycle stress of 30 MPa in both methods of welding, fatigue cracks in welded joints are not formed even after $2 \cdot 10^6$ load cycles. Instead, at a load of 35 MPa, fatigue cracks of a critical length (3 mm) were detected in places of transition from the weld to base metal, both in a stationary welding process, as well as in PAW, approximately at the same load cycles (respectively 1.8 and $1.86 \cdot 10^6$ cycles). With an increase in stresses to 40 MPa, a number of cycles, at which a fatigue crack was formed, significantly decreased. But

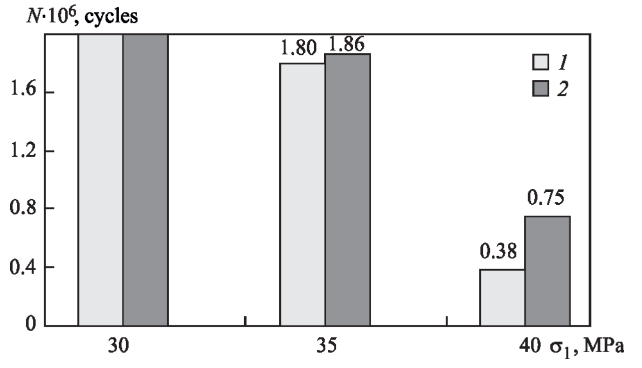

Figure 7. Resistance of T-welded joints of 13KhGMRB steel to fatigue cracks formation at cyclic bending load: *1* — stationary process; *2* — PAW

still, in PAW, they were approximately 2 times higher than in the stationary process (respectively, 0.38 and $0.75 \cdot 10^6$ cycles). In our opinion, such a difference can be explained by the formation of smoother transitions from the weld to base metal in PAW and a corresponding decrease in the level of stress concentration in this welded joint zone.

CONCLUSIONS

1. In pulsed-arc welding, compared to the stationary process, some changes occur in the formation of structures in the weld and HAZ metal of welded joints of low-alloy heat-strengthened 13KhGMRB steel. The structure of metals becomes more hardened. In the weld metal, an upper and mainly lower bainite (sorbite, 274 *HV*) with the hardness of 317–336 *HV* is formed. In the region of coarse HAZ grain, a martensitic structure with a hardness of 446–488 *HV* (bainite, 383 *HV*) is observed.

2. At the change in the welding process, the values of static strength and ductility of the welds metal of welded joints are comparable and are within $\sigma_{0.2}$ = = 713–740 MPa, σ_t = 786–800 MPa, δ_5 = 16–19 %, ψ = 59–67 %.

3. The influence of the arc welding process on the values of impact toughness of the welds and HAZ metal is ambiguous. Higher values of impact toughness are typical of the welds metal of welded joints made using the traditional arc welding process, namely using an arc that burns stationary. Traditionally, as the test temperature is reduced, the values of *KCV* decrease and at the test temperature of minus 40 °C, they are 43–49 J/cm^2, regardless of the welding process. The similar regularities concerning changes in impact toughness depending on the welding method are also observed for HAZ metal of welded joints. The exception is the results of testing specimens at a test temperature of minus 40 °C. At this test temperature, the specimens made from the welded joints produced using pulsed-arc welding, have the highest values of KCV_{-40} (108 J/cm^2).

4. The resistance of the welds and HAZ metal of welded joints, regardless of the welding method is at a high level ($Kq \geq 84$ MPa√m).

5. Due to the formation of a tempered martensitic structure in a pulsed-arc welding in the HAZ metal of welded joints of heat-strengthened 13KhGMRB steel, their resistance to cold cracks formation deteriorates. In order to avoid the formation of such cracks in welded joints, the heating of such joints should be increased from 90 to 120 °C.

6. The results of testing welded T-joint specimens of heat-strengthened 13KhGMRB steel on cyclic bending load showed that welded joints in pulsed-arc welding due to the formation of smoother transitions from the weld to base metal and a corre-sponding decrease in the level of stress concentration have an increased resistance to fatigue cracks formation.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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