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INFLUENCE OF ARC WELDING TECHNOLOGY ON RESISTANCE OF WELDED JOINTS OF 06G2BDP STEEL TO COLD AND HOT CRACKING, FATIGUE AND BRITTLE FRACTURE

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ABSTRACT

The paper studies the influence of arc welding technological processes on the resistance of welded joints of sparcely-alloyed weathering 06G2BDP steel to cold and hot cracking and brittle and fatigue fracture. With the help of the Implant method and using the technological Tekken sample, the conditions for cold cracking were evaluated and the methods of their elimination were recommended. It is shown that with the use of mechanized welding in shielding gases, solid-section and flux-cored wires provide high technological strength of welded joints in terms of hot cracking in a wide range of welding modes. On the other hand, when using coated electrodes, this range is narrowed, and at $V_{def} \geq 20$ mm/min, joints are prone to the formation of this defect. The results of studies on the evaluation of welded joint resistance to brittle fracture indicate high values of the stress intensity factor K_Q for both the weld and HAZ metal. The endurance limit of T-joints when tested by cyclic loading was determined, which is $[\sigma]_{-1} = 35$ MPa.

KEYWORDS: weathering steel, welded joints, cold cracks, hot cracks, brittle fracture, cyclic loading, fatigue fracture

INTRODUCTION

Publications of recent years indicate an increase in the use of weathering sparcely-alloyed steels in metal structures of bridges and other building structures [1–3]. Such trends are characteristic of developed countries, such as the USA, Japan, Italy and Great Britain [4–7]. In view of the interest of domestic bridge builders in the use of weathering rolled steel for span structures of bridges in Ukraine, sparcely-alloyed weathering 06G2BDP steel with an increased phosphorus content of up to 0.05 % is proposed [3]. The conducted studies of the impact of thermal welding cycles on the change in the structure and mechanical properties of the HAZ metal of welded joints of the mentioned steel made it possible to establish a range of optimal cooling rates, at which static strength and impact toughness grow due to the formation of a bainitic-martensitic structure in this area of a joint [3, 8]. In [9], based on the carried out studies of the influence of mechanized arc welding in shielding gases and automatic submerged arc welding methods on the mechanical properties and structure of welded joints of 06G2BDP steel of C390 and C500 strength classes, welding consumables are proposed that provide the required set of mechanical properties of the weld metal at the level of the base metal of the abovementioned strength classes. At the same time, it is known that an increased content of phosphorus in steel can deteriorate its weldability.

The main difficulties in welding low-carbon steels are related to the need in preventing the probability of cold cracking in the HAZ and weld metal, as well as structures that sharply reduce the resistance of welded joints to brittle and fatigue fracture. Hardening structures in the HAZ and weld metal, hydrogen in these areas of a welded joint and stresses of the first kind caused by the welding process and the rigidity of joint fixation have a decisive impact on cold cracking [10–14].

The most common defects in welded joints, in addition to cold cracks, include intercrystalline fracture — hot cracking. Hot cracks are one of the types of high-temperature fracture. They can arise with an unfavorable combination of factors associated with a deterioration in the deformation capacity of the metal due to the appearance of low-melting eutectics, defects in the crystalline structure, precipitations of brittle phases in the structure, as well as under the effect of external and internal stresses. Hot, or crystallization cracks represent micro- and macroscopic discontinuities originating in the crystallization interval of the metal. The temperature at which they are formed depends on the chemical composition of the weld metal. In welding of carbon steels, hot cracks are formed, as a rule, in the temperature range from 1200 to 1350 °C. Hot cracks are an unacceptable defect of a welded joint, which can be the cause of fracture of structures during manufacture or operation.

The ability of weld metal to perceive elastic-plastic deformations at high temperatures in the welding process without hot cracks determines its technological strength. The high probability of defects in welded joints of metal structures made it necessary to assess the probability of brittle fracturing of welded structures depending on their load conditions, location of a defect, its shape and size in order to ensure the reliability of their operation. It became possible to solve this problem due to the use of criteria and methods of fracture mechanics. They are based on tests of specimens with artificial defects, the sizes of which are stable during manufacture and are subjected to analytical interpretation, in contrast to natural technological defects, the stable sizes of which are very difficult to predict.

Therefore, the aim of the work was to study the influence of welding technological processes on the resistance of welded joints of 06G2BDP steel to delayed, intercrystalline, brittle and fatigue fracture. To achieve the set aim, the following research tasks were solved in the work based on the use of specialized research methods:

- the influence of the technological parameters of arc welding (preheating temperature, welding input energy, etc.) and the content of diffusible hydrogen in the deposited metal on the resistance of welded joints of 06G2BDP steel to cold cracking (delayed fracture) was determined;
- the resistance of welded joints of the studied steel to hot cracking (intercrystalline fracture) was evaluated;

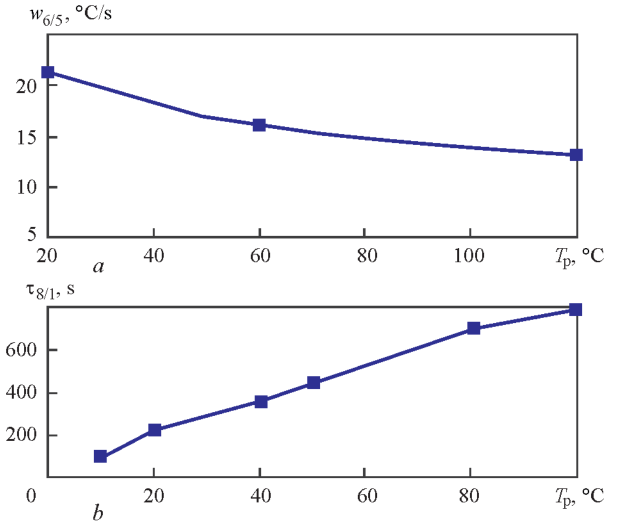

Figure 1. Influence of preheating temperature on cooling rate of specimens in the temperature range of 600–500 °C (*a*) and their period of stay in the temperature range of 800–100 °C (*b*)

- the influence of arc welding parameters on the resistance of welded joints to brittle and fatigue fracture under the cyclic load was studied.

RESEARCH PROCEDURE

Studies of the tendency of the HAZ metal of welded joints of 06G2BDP steel to delayed fracture depending on the content of diffusible hydrogen in the weld metal and the value of critical stresses were carried out using the Implant method [10]. Cylindrical specimens-inserts manufactured of 13 mm thick 06G2BDP steel with the following chemical composition in %: 0.07 C; 1.36 Mn; 0.08 Si; 0.3 Cr; 0.03 Nb; 0.47 Cu; 0.011 S; 0.053 P were subjected to tests. The same steel was used in manufacturing technological plates of 300×250 mm, into which specimens-inserts were inserted.

Manual arc welding was performed with ANP-10 electrodes of 4.0 mm diameter, which provided the indices of yield strength of the weld metal approximately at the level of this steel and were 539–550 MPa. The following mode was used for welding: I_w = 160–180 A, U_a = 26–27 V, V_w = 7.5 m/h. The cooling rate of the HAZ metal was regulated due to preheating. At the same time, the initial temperature of the plates varied from 20 to 90 °C, and the cooling rate of welded joints in the temperature interval of 600–500 °C ($w_{6/5}$) varied in the range from 21 to 14 °C/s. Dependencies characterizing the effect of the preheating temperature on the cooling rate of the specimens and the period of their stay in the temperature range of 800–100 °C ($\tau_{8/1}$) are shown in Figure 1 [11]. The content of diffusible hydrogen in the deposited metal, which was determined by the method of pencil samples using a mixture of glycerin and distilled water in a ratio of 1:4 as a blocking substance, was changed due to electrodes with different coating humidity. For this purpose, the electrodes were moistened or calcinated at different temperatures.

Resistance to cold cracking of welded joints was evaluated using the well-known Tekken technological sample [12].

The presence of cold cracks in it was detected within 24 h after welding by an external inspection of the weld surface and on the macrosections, if they occurred in depth without exit to the surface of a joint. The critical cooling rate of welded joints or the concentration of diffusible hydrogen in the deposited metal was used as a test criterion, at which the total length of cracks in the root, on the surface, and in the weld or HAZ section did not exceed 50 %.

Manual arc welding of Tekken technological samples was performed with coated ANP-10 electrodes of 4.0 mm diameter in the same mode as in welding by the Implant method. Mechanized welding in shielding gases was performed with the solid-section NiMo1-IG wire and the flux-cored Filarc PZ 6114S wire of 1.2 mm diameter. Welding with the flux-cored wire was performed in CO_2, and with the solid-section wire — in shielding gases 82 % Ar + 18 % CO_2. The modes of mechanized welding were the following: I_w = 180–200 A, U_a = 26–28 V, V_w = 14–16 m/h. Both manual arc and mechanized welding were performed without preheating.

The succeptibility of the weld metal to hot cracking was evaluated by the method of tests during static bending of welded joints in the process of their welding. At the same time, the critical deformation rate V_{def}, which leads to hot cracking, was determined. The welding modes are indicated above, only the welding speed was a variable. In manual arc welding, it was changed in the range of 9.5–12 m/h and in mechanized welding — in the range of 15–20 m/h.

Standard specimens of 120×20×10 mm were used to evaluate the resistance of welded joints to brittle fracture, which were tested in three-point bending according to the methods of fracture mechanics.

For comparison, one series of specimens was manufactured from the base metal and other — from butt joints produced by mechanized welding in a gas mixture of 82 % Ar + 18 % CO_2 with the solid-section NiMo1-IG wire and the flux-cored Filarc PZ 6114S wire in CO_2.

The notch and the tip of a fatigue crack in the specimens were located in the weld or in the HAZ metal. The specimens were loaded in the Friedland installation, while the loading rate was 4–18 mm/min.

In order to evaluate the resistance of welded joints to fatigue fracture [15], the studies were conducted using T-specimens with a one 50 mm height transverse stiffener, which was welded-on to a 13 mm thick plate in two fillet welds with full penetration (Figure 2).

Mechanized welding of T-specimens was performed with the solid-section BOEHLER NiMo1-IG wire of 1.2 mm diameter in a gas mixture of 82 % Ar + 18 % CO_2. After welding, the specimens were subjected to the cyclic bending load (UMP-02 installation) with a frequency of 14 Hz at different symmetrical cycle stresses of 45, 40 and 35 MPa. During the fatigue tests, a number of load cycles was recorded, during which fatigue cracking of a critical size (3 mm) occurred.

RESULTS OF THE WORK AND THEIR DISCUSSION

Using the Implant method, it was shown that the stress, at which delayed fracture of 06G2BDP steel specimens is not observed is 440 MPa. At higher

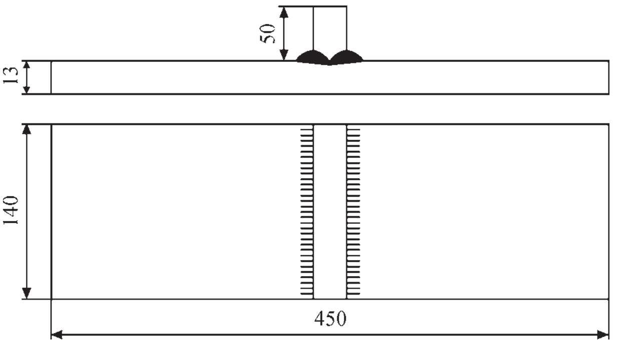

Figure 2. Schematic representation of T-specimen for fatigue tests

values of loads, flowability of the specimens was observed. As was shown by the results of previously conducted metallographic examinations, under the given cooling conditions, in the HAZ metal, a bainitic structure is formed. Based on that, it can be assumed that with a limited amount of diffusible hydrogen in the deposited metal of up to 0.8 ml/100 g, the HAZ metal with this structure does not undergo hydrogen embrittlement and has a high resistance to cold cracking. Using the same method, it was established that the critical stresses, at which delayed fracture does not occur, decrease to 220 MPa when $[H]_{diff}$ is increased to 3.8 ml/100 g, and increase to 340 MPa when its value is reduced to 1.8 ml/100 g (Figure 3).

With an increase in the content of diffusible hydrogen in the deposited metal from 0.8 to 3.8 ml/100 g, the risk of cold cracking in the HAZ metal of welded joints grows. To exclude the probability of cracking in such joints, the level of residual stresses should not exceed 440 and 360 MPa. It is possible to improve the resistance of the HAZ metal of welded joints to delayed fracture thanks to the use of preheating. Thus, it was established that at $[H]_{diff}$ = 3.8 ml/100 g, preheating (T_p) to a temperature of 60 °C makes it possible to increase the level of critical stresses to 380 MPa, and at T_p = 90 °C, to σ = 420 MPa.

Therefore, with a limited content of diffusible hydrogen in the weld, the HAZ metal is not prone to delayed fracture. According to these conditions, welded

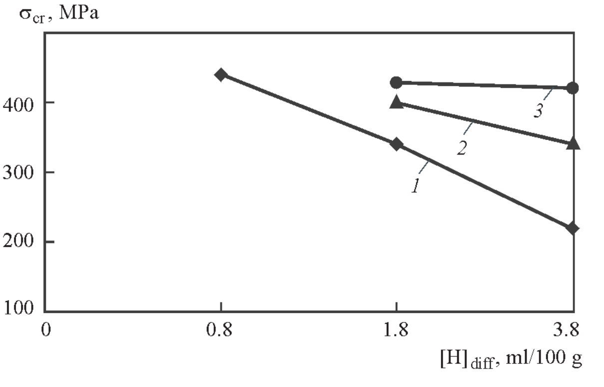

Figure 3. Influence of diffusion hydrogen on resistance to delayed fracture of HAZ metal of 06G2BDP steel: *1* — without heating; *2* — T_p = 60 °C; *3* — T_p = 90 °C

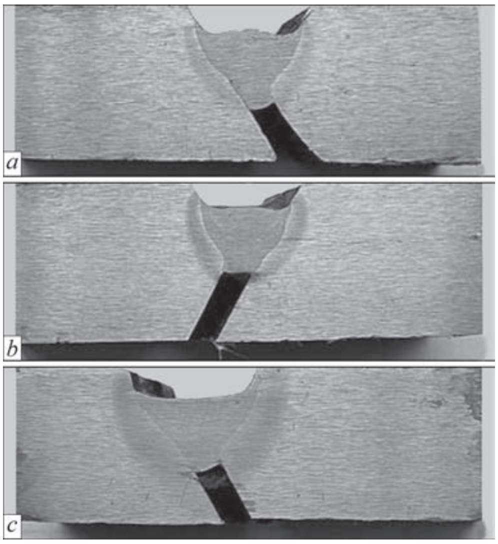

Figure 4. Macrosections of welded joints of Tekken samples of 06G2BDP steel, produced: *a* — with the solid-section NiMo1-IG wire in a gas mixture of 82 % Ar + 18 % CO_2; *b* — with the flux-cored Filarc PZ 6114S wire in CO_2; *c* — with coated ANP-10 electrodes

joints of this steel have sufficient resistance to cold cracking.

The analysis of macrosections cut out from Tekken samples within 24 h after making the reference welds showed that in welding without preheating, all the abovementioned welding methods and welding consumables provide sufficiently high resistance of welded joints to cold cracking, regardless of the alloying weld metal (Figure 4).

It was established that sparcely-alloyed welding consumables, namely ANP-10 electrodes and the flux-cored Filarc PZ 6114S wire, as well as the solid-section NiMo1-IG wire alloyed with nickel and molybdenum under the conditions of manual arc and mechanized welding in shielding gases, provide high resistance of welded joints of 06G2BDP steel to cold cracking.

The obtained data on the resistance of welded joints of 06G2BDP steel to hot cracking show (Table 1) that during mechanized welding in shielding gases with both flux-cored as well as solid-section wire, sufficient technological strength is provided in a wide range of loading rates. On the other hand, under the conditions of using ANP-10 coated electrodes at a deformation rate $V_{def} \leq 20$ mm/min, welded joints of 06G2BDP steel have a margin of technological strength. An increase in the deformation rate to the values higher than 20 mm/min leads to hot cracking, the resistance to which deteriorates.

The conducted studies using the criterion of fracture mechanics established that the highest K_Q indices are typical for the base metal. Their values depend on the test temperature of the specimens and decrease from 103.8 MPa√m (test temperature of 20 °C) to 90.7 and 86.0 MPa√m at (–20 and –40 °C), respectively. Somewhat lower, but still rather high K_Q values were obtained from the results of tests of the specimens, in which the tip of the fatigue crack was located both in the center of the weld metal, as well as in the HAZ metal of welded joints.

Regardless of the welding method, the studied welding consumables and applied welding modes provide fairly close K_Q indices both for the welds as well as for HAZ of welded joints. Thus, for the weld metal, produced by the flux-cored Filarc PZ 6114S wire at test temperatures of –40, –20 °C and 20 °C, the average K_Q values are, respectively: 82.2; 84.9 and 96.2 MPa√m, and for the weld metal produced by the solid-section NiMo1-IG wire, at similar test temperatures, the average K_Q values are 81.6; 84.4 and 94.9 MPa√m, respectively (Figure 5, *a*).

A similar dependence of K_Q indices on the temperature of specimen tests, namely, a decrease in their values as the temperature drops, was also observed in the specimens where the tip of the notch fell on

Table 1. Technological strength of welded joints of 06G2BDP steel

Number	Welding variant	Deformation rate V_{def}, mm/min	Presence of hot cracks
1	Mechanized with the flux-cored Filarc PZ 6114S wire of 1.2 mm diameter in CO_2	10.3	Absent
		15	
		28.6	
2	Mechanized with the solid-section NiMo1-IG wire of 1.2 mm diameter in a mixture of 82 % Ar + 18 % CO_2	28.2	
		37.1	
3	Manual arc with coated ANP-10 electrodes of 4.0 mm diameter	18.3	
		25.5	
		32.7	
		52	

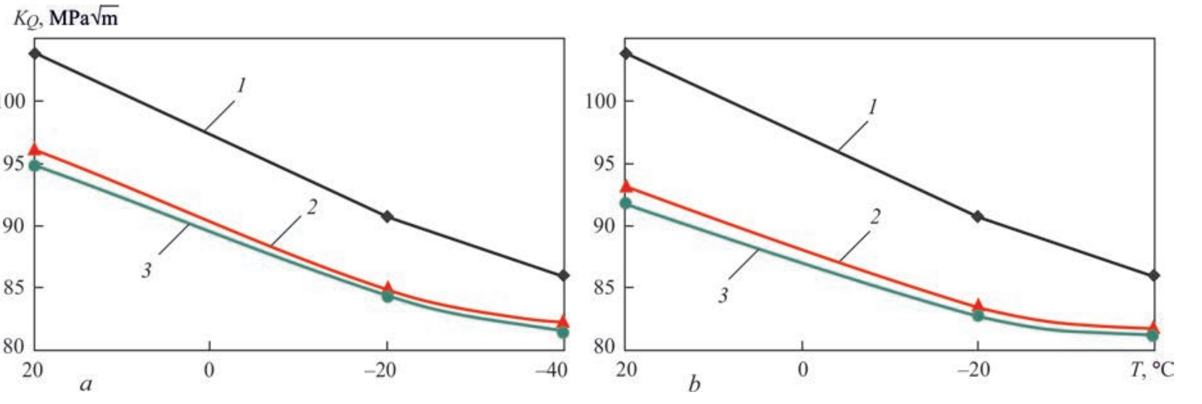

Figure 5. Dependence of values of critical stress intensity factor K_Q on test temperature for the base metal of 06G2VDGI steel (*a*, *b* — *1*) of weld (*a*) and HAZ metal (*b*) of welded joints produced with the solid-section NiMo1-IG wire in a gas mixture of 82 % Ar + 18 % CO_2 (*2*) and Filarc PZ 6114S in CO_2 (*3*)

the HAZ metal of welded joints. In terms of the value, they are somewhat lower compared to K_Q indices of the weld metal, but they are also at a high level and in welding with the flux-cored Filarc PZ 6114S wire they were 81.7; 83.5 and 93.1 MPa√m, and in welding with the solid-section wire — 81.2; 82.8 and 91.7 MPa√m at test temperatures of –40, –20 and 20 °C, respectively (Figure 5, *b*).

The results of fatigue resistance studies showed that at symmetrical cycle stresses of 45 and 40 MPa, cracks of critical length were formed in the T-specimens along the fusion line. Namely: at σ_{-1} = 45 MPa, a fatigue crack formed after *N* = 999,000 load cycles, at σ_{-1} = 40 MPa, it was observed after *N* = 1,670,000 load cycles.

Under the test conditions at the symmetric cycle stress of σ_{-1} = 35 MPa, the T-joint of 06G2BDP steel remained non-destructive after $N = 2.1 \cdot 10^6$ load cycles. Thus, it can be assumed that for welded joints of 06G2BDP steel, the endurance limit is at the level of σ_{-1} = 35 MPa.

CONCLUSIONS

Studies of the influence of arc welding technological processes on the resistance of welded joints of corrosion-resistant 06G2BDP steel to cold and hot cracking as well as brittle and fatigue fracture established the following:

● the use of sparcely-alloyed ANP-10 electrodes with a content of diffusible hydrogen in the deposited metal limited to $[H]_{diff}$ = 0.8 ml/100 g in manual arc welding, flux-cored Filarc PZ 6114S wire, as well as solid-section NiMo1-IG wire alloyed with nickel and molybdenum in mechanized welding provide high resistance to cold cracking in the HAZ and weld metal of welded joints. With an increase in the content of diffusible hydrogen to $[H]_{diff}$ to 3.8 ml/100 g, it is necessary to apply preheating to T_p = 90 °C;

● the abovementioned welding consumables during mechanized welding in shielding gases provide sufficient technological strength in a wide range of loading rates. On the other hand, in manual arc welding with the coated ANP-10 electrodes, the margin of technological strength is ensured under the conditions of the deformation rate of $V_{def} \leq 20$ mm/min;

● high resistance of both weld and HAZ metal to brittle fracture is ensured also when using mechanized welding in shielding gases with the flux-cored Filarc PZ 6114S wire and solid-section NiMo1-IG wire. Indices of the stress intensity factor reach the values of K_Q = 96 MPa√m. A reduction in the test temperature to –40 °C leads to a decrease in the stress intensity factor by 15 %, K_Q = 82 MPa√m;

● cyclic load tests show that the endurance limit of welded joints of 06G2BDP steel is symmetrical cycle stresses of σ_{-1} = 35 MPa.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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