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IMPACT OF THERMAL CYCLES OF WELDING ON FORMATION OF THE STRUCTURE AND PROPERTIES OF CORROSION-RESISTANT STEEL 06G2BDP

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High-strength low-alloy steels with high service properties, in particular, resistance to atmospheric corrosion, become ever wider applied in mechanical and industrial engineering. Their application allows not only reducing specific weight of metal structures, but also increasing their reliability and operating life. In view of that, on the base of steel 06G2B, steel 06G2BDP with higher corrosion resistance was developed. In order to improve its corrosion resistance, copper and phosphorus content in the steel was increased. The work deals with the issue of the impact of thermal cycles of welding on mechanical properties and structure of HAZ metal in welded joints of atmospheric-resistant steel 06G2BDP. It is shown that as to the values of static strength, ductility and impact toughness steel 06G2BDP is not inferior to steel 06G2B, and is superior to steel 10KhSND. Its application is rational as an alternative to the above-mentioned steels in fabrication of modem metal structures by gas-shielded manual and mechanized arc welding in the range of HAZ metal cooling rates specified for them. 13 Ref., 2 Tables, 4 Figures.

Keywords: corrosion-resistant steel, thermal cycle of welding, heat-affected zone, structure, properties

High-strength low-alloy steels with high service characteristics: strength, toughness, resistance to atmospheric corrosion are becoming ever more widely used in mechanical engineering and industrial construction, in particular, in bridge construction. Their use allows not only reducing specific weight of metal structures, but also increasing their reliability and operating life. The results of the inspection of state of the metal structures of bridges with steel main and transverse beams and a steel reinforced concrete roadway show that the main type of their damages is a reduction in the cross-sectional sizes of girths and beam walls as as result of corrosion, which significantly reduces bearing capacity and serviceability of bridges [1]. The combination of sometimes inefficient design and technological solutions coupled with the use of conventional construction steels in bridges in the former times strengthen and accelerate the corrosion processes in the structure [2].

A large number of research works was devoted to corrosion resistance of low-alloy steels in atmospheric conditions. In particular, they indicate that limited atmospheric-resistant low-alloy steels contain elements which under the influence of the ordinary atmosphere, form a film of corrosion products on the surface, which has protective properties. The steels of this type were developed in the USA and were originally used in the bodies of railway cars. In the 1960s, such steels began to be used in other structures, such as steel reinforced concrete bridges [3].

The influence of the chemical composition on the rate of atmospheric corrosion of the metal was considered in many works [4–6]. It was found that an increased content of copper, phosphorus, chromium, as well as nickel and molybdenum improves the resistance of steel to atmospheric corrosion [4]. In ASTM G101 the index is presented, by which it is possible to judge about the resistance of steel to atmospheric corrosion: I = 26.01 Cu + 3.88 Ni + 1.20 Cr + 1.49 Si + 17.28P – 7.29 CuNi – 9.10 NiP – 33.39 Cu.

The scale of application of weather-resistant steels in bridge structures in different countries is different. In Germany and France such bridges are rare, while in Italy and Great Britain their number is the largest. In the USA and Japan about 50 % of metal and combined bridges are made of weather-resistant steels [7–9].

In Ukraine, during the last fifteen years, steels 06GB, 06G2B and 10KhSND were introduced and successfully used in the construction of critical welded structures. Sparsely-alloyed steels of high strength and cold resistance differ favorably from steels, which are usually used in the manufacture of domestic metal structures. Steels of this class belong to the steels with carbonitride strengthening. They are low-carbon (C = 0.04–0.08 %) and sparsely-alloyed, at the same time having bal-

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Table 1. Chemical composition of steels, wt.%

Steel	C	Si	Mn	P	S	Al	Cr	Mo	Ni	Cu	Nb	Ti
06G2BDP	0.08	0.35	1.4	0.05	0.012	0.02	0.30	0.02	0.30	0.3	0.03	0.02
06G2B	0.08	0.25	1.3	0.025	0.01	0.02	–	0.1	–	0.3	–	–
10KhSND	≤0.12	0.8	0.8	0.03	0.035	–	0.6	–	0.5	0.4	–	–

anced mechanical and technological properties [10–12]. Corten A and Corten B differ from foreign steels in their lower content of such elements as nickel, chromium and molybdenum. At present, these steels were successfully used in the construction of a number of critical objects, such as blast furnace at the Kryvyi Rih ore-mine combine, oil storage tanks with a capacity of 50000 and 75000 m^3, separate elements of bridge structures through the entrance to the harbor of Podilsk bridge transition.

Taking into account the interest of bridge builders in the use of weather-resistant rolled metal for girder structures, on the basis of steel 06G2B, steel 06G2BDP with a high resistance to corrosion was created [13]. To improve a corrosion resistance in steel, the content of copper and phosphorus is increased. As is mentioned above, phosphorus improves strength as well as atmospheric corrosion resistance, especially in contact with copper. At the same time, the deformation properties of steel are deteriorated. In addition, it is known that an increased content of phosphorus in steel can reduce its cold resistance and deteriorate the weldability. Therefore, the aim of this work was to study the impact of thermal welding cycles on the mechanical properties and structure of the HAZ metal of welded joints of steel 06G2BDP.

Procedure of investigations. As the object of investigation the steels were selected, the chemical composition and mechanical properties of which are given in Table 1 and Table 2.

In accordance with GOST 9.911–89 and GOST 9.908–85 in the laboratory conditions of the E.O. Paton Electric Welding Institute, comparative investigations of corrosion resistance of the proposed steel and rolled steels 10KhSND and 06G2B were performed, which are widely used in bridge construction. The standard GOST 9.911–89 regulates the method of comparative accelerated corrosion tests of low-alloy steels which are applied without the protection against atmospheric corrosion. This method of investigations can also be used to obtain comparative data on corrosion resistance of carbon and low-alloy steels used with protective coatings. The essence of the method is to accelerate the corrosion process of formation of protective layers of corrosion products on the steel surface. Acceleration of the corrosion process is achieved by increasing the relative humidity of air and temperature under the action of sulfur dioxide, periodic condensation of moisture, as well as alternating wetting of the specimens surface with electrolyte and its subsequent drying.

The specimens of investigated steels in the amount of not less than 3 pcs (100×50×1.5 mm) were compared with the specimens of the reference steel. In this study, as a reference the specimens of 10KhSND steel were used. The tests were performed cyclically with periodic changes of the first and second stages of the cycle. The duration of one cycle is 168 h. The total duration of the tests is 7 cycles (1176 h). The first stage of the cycle proceeds as follows: in the atmosphere of SO_2 at a temperature of 40 °C for 7 h and then at a temperature of 20 °C for 64 h. The second stage of the cycle proceeds as follows: periodic immersion of the specimens in the solution of $5\cdot10^{-6}$ mol/l of a sulfuric acid for 97 h (10 min in the solution and 50 min in air, including at air flow at a temperature of 60 °C) in the installation «corrosion wheel».

The values of corrosion and corrosion resistance were determined according to GOST 9.908–85. As the main value of a continuous corrosion a decrease in mass per unit area of the specimens and the rate of loss of mass of the specimens was accepted.

The dependence of mechanical properties on the cooling rate of the HAZ metal in the temperature range of 600–500 °C was studied using the model specimens of the size 120×12×12 mm, which were heated and cooled in accordance with the thermal cycles of arc welding in the specialized equipment MCR-75. The heat treatment process was as follows. Initially, the specimens were heated to the temperature of 1200–1300 °C, which are characteristic of the area of overheating of HAZ of welded joints. The heating rate of the specimens was 150–170 °C/s, which corresponds to the conditions of heating the metal in the heat-affected-zone during arc welding processes. At this temperature, the specimens were kept for approximately 2 s, and then forcibly cooled. To provide different cooling rates of the heated specimens, the conditions of their cooling were changed. Thus, to provide cooling rates in the range from 3.0 to 7.5 °C/s, the specimens were cooled by cooling the copper clamps of the installation with running water of different flow intensity. Higher cooling rates were achieved as a result of additional blowing of the specimens with inert gas, which allowed regulating $w_{6/5}$ from 8.0 to 20.0 °C/s by changing intensity of gas flow. The heating-cooling rate of the specimens was controlled by a chromel-alumel thermocouple with a diameter of 0.5 mm.

Table 2. Mechanical properties of steels

Steel	σ_y, MPa	σ_t, MPa	δ_5, %	KCV^{-40}
06G2BDP	608	684	22	355
06G2B	490	590	20	98
10KhSND	390	530–660	19	29

From each batch of heat-treated model specimens, standard specimens were manufactured to perform mechanical tests and determination of impact toughness of the HAZ metal. For static tensile tests, the specimens of type II (3 specimens for each cooling rate) and for impact bending the specimens of type IX were manufactured in accordance with GOST 6996–96. The impact toughness was determined when testing Charpy specimens with a sharp notch at the testing temperatures of 20, –20 and –40 °C. According to the results of the tests, the effect of cooling rate on the change of the following indices of the HAZ metal was evaluated: static strength (σ_y and σ_t, MPa); ductility (δ_5 and ψ, %) and toughness (*KCV* J/cm^2).

Metallographic examinations were performed using a microscope «Neophot-32», the microhardness of separate structural components and the integral hardness of the metal was measured in the durometer M-400 of the LECO Company at the loads of 100 g ($HV_{0.1}$) and 10 kg (HV_{10}). The specimens for investigations were prepared by the standard method using diamond pastes of different dispersion, the detection of microstructure was performed by chemical etching in 4 % alcoholic solution of nitric acid.

Results and discussion. According to the thermokinetic decay diagrams of supercooled austenite, steels 06G2B and 06G2BDP under normal cooling conditions have mainly a bainitic structure. However, steel 10KhSND has a ferritic-pearlitic structure, which causes lower mechanical properties as compared to steels 06G2B and 06G2BDP. Under the conditions of accelerated cooling rates typical for the thermal cycle of welding, the structure of steel 06G2B in a quite wide range of cooling rates of the HAZ metal remains predominantly bainitic. At the same time, for steel 06G2BDP, due to additional alloying with phosphorus and copper, the area of bainitic transformation is slightly shifted, which is reflected in a greater tendency to bainite formation and, as a consequence, increased mechanical properties as compared to steel 06G2B. For steel 10KhSND the formation of pearlitic-bainitic structure at the cooling rates corresponding to the thermal cycle of welding is characteristic. This fact negatively affects the characteristics of cold resistance of this steel.

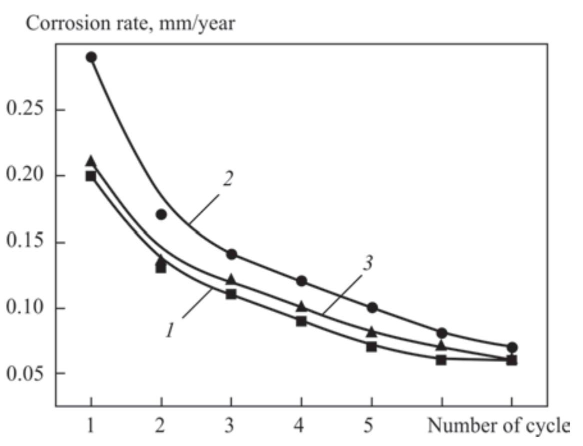

Figure 1. Change of corrosion rate of steel in the course of tests: *1* — 06G2BDP; *2* — 10KhSND; *3* — 06G2B

According to the results of the tests on corrosion resistance, it was found that its values for the investigated steel 06G2BDP are 20 % higher than in steel 10KhSND, and not inferior to steel 06G2B. This is evidenced by the data on the change in the corrosion rate shown in Figure 1, especially in the first cycles of investigations.

The results of metallographic examinations indicate that due to heat treatment in the form of hardening and tempering, in the studied steel 06G2BDP ferritic-carbide structure is formed (Figure 2, *a*) with a grain size of about 4–20 μm and a hardness *HV*206. This, in turn, provides high indices of static strength $\sigma_y > 600$ and $\sigma_t > 690$ MPa, ductility $\delta_5 > 21$ % and $\psi > 72$ % and impact toughness of the HAZ metal of steel 06G2BDP, which significantly exceed the normative values and similar indices of steel 10KhSND.

The dependences, characterizing changes in the indices of static strength and ductility in the simulated HAZ metal of steel 06G2BDP under the effect of thermal welding cycle are shown in Figure 3. For comparison, the given results of tests of the HAZ metal of steel 06G2B and 10KhSND are given.

The results of the carried out investigations indicate that at the cooling rate $w_{6/5} = 3$ °C/s in the temperature range of 600–500 °C, the yield strength of the HAZ metal decreases as compared to the initial state, namely $\sigma_{0.2}$ from 608 to 490 MPa, with an increase of $w_{6/5}$ to 14 °C/s, the yield strength increases to 544 MPa and up to 565 MPa at $w_{6/5} = 23$ °C/s. The static tensile strength σ_t decreases slightly to 657 MPa at $w_{6/5} = 3$ °C/s, and then it increases to 710 MPa at $w_{6/5} = 25$ °C/s. At the same time, the ductile properties of the simulated HAZ metal as compared to the initial state are changed insignificantly (changes do not exceed 5 %). A similar trend in terms of changes in the mentioned mechanical properties is characteristic also to the HAZ metal of steel 06G2B and 10KhSND, but the absolute values of these indices are lower.

During tests of specimens with a sharp V-shaped notch for impact bending, it was found that the impact toughness of the HAZ metal of steel 06G2BDP decreases relatively to the base metal (Figure 4). The most significant decrease in *KCV* values is observed in the specimens that were cooled at a rate of $w_{6/5} =$ $= 3$ °C/s (from 355 to 86 J/cm^2 at a test temperature of 20 °C, and from 316 to 10 J/cm^2 at a temperature of –40 °C). With an increase in the cooling rate to 14 °C/s, the values of impact toughness of the HAZ metal grow significantly to 270 J/cm^2 at the test temperature of 20 °C and only to 31 J/cm^2 at the test temperature of the specimens being –40 °C. A further increase in the cooling rate $w_{6/5}$ to 23 °C/s leads to a decrease in the impact toughness of the specimens tested at a temperature of 20 °C to $KCV^{20} = 180$ J/cm^2, at that time continued growing slightly and reached the values of KCV^{-40} = 35 J/cm^2.

It should be noted that the values of mechanical properties and impact toughness of the HAZ metal of steel 06G2B, on the base of which the corrosion-resistant steel 06G2BDP was developed, are almost on the same level with it. Regarding the values of impact toughness of the HAZ metal of the model specimens in steel 10KhSND a significant difference in their behavior under the action of thermal welding cycles can be distinguished as compared to sparsely-alloyed steels 06G2B and 06G2BDP. Namely, *KCV* values of the HAZ metal of the mentioned steel during the tests at the temperatures of 20 and –40 °C react weakly to changes in the cooling rate. This is evidenced by the fact that the impact toughness of the specimens of steel 10KhSND, which were tested at a temperature of 20 °C, are in the range of 55–75 J/cm^2, and at a temperature of –40 °C it is 14–22 J/cm^2.

Changes in the mechanical properties of the HAZ metal of steel 06G2BDP are predetermined by different structural transformations in the range of the investigated cooling rates. This is evidenced by the results of metallographic examinations. Metallographic examinations established that in the area of overheating in the HAZ metal of steel 06G2BDP at a cooling rate $w_{6/5}$ = 3 °C/s, a structure formed consisting of a ferritic-pearlitic mixture with ferrite fringes (Figure 2, *b*), the average grain size is of the order of 300 μm. The hardness of such metal is *HV* 270. When $w_{6/5}$ rises to 14 °C/s, an equilibrium bainite structure is formed with 70 % content of upper bainite and 30 % of lower one. The grain size decreases and is equal to 100 μm, and hardness increases to *HV* 303.

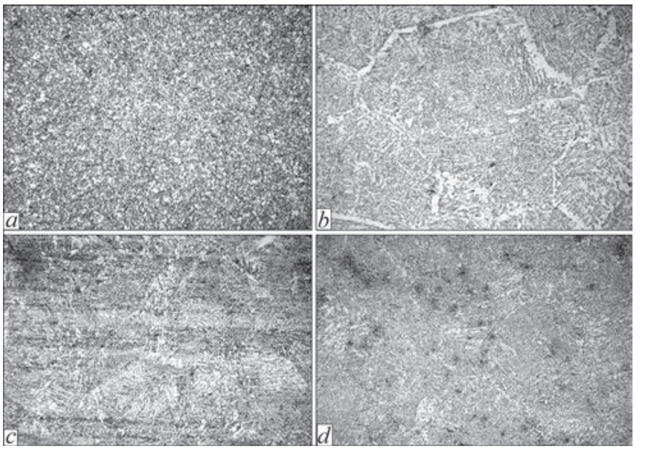

Figure 2. Microstructure (×200) of steel 06G2BDP depending on the value of cooling rate $w_{6/5}$: *a* — base metal; *b* — 3; *c* — 14; *d* — 23 °C/s

At a further increase in the cooling rate to $w_{6/5}$ = = 23 °C/s in the simulated HAZ metal, a structure is formed consisting of a mixture of upper (30 %) and lower bainite (70 %). Due to that, the hardness of the metal ranges from *HV* 232 to *HV* 340, which, in turn, leads to an increase in the values of its static strength. The grain size is reduced to 70 μm.

It is shown that a decrease in the static strength and impact toughness of the HAZ metal of steel 06G2BDP at the cooling rate $w_{6/5}$ = 3 °C/s is predetermined by a significant grain growth (to 300 μm) and the formation of ferritic-pearlitic structure with fringes. An increase

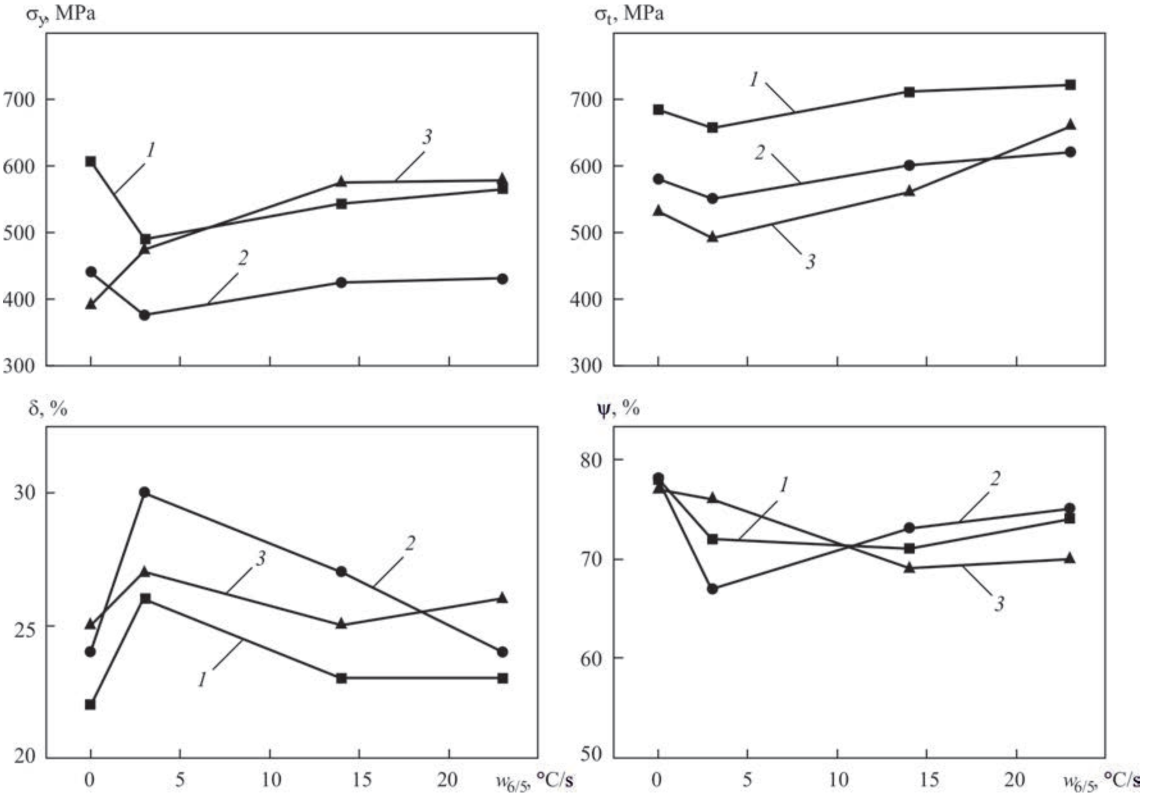

Figure 3. Mechanical properties of HAZ metal of the investigated steels depending on the value of cooling rate $w_{6/5}$: *1* — 06G2BDP; *2* — 06G2B; *3* — 10KhSND

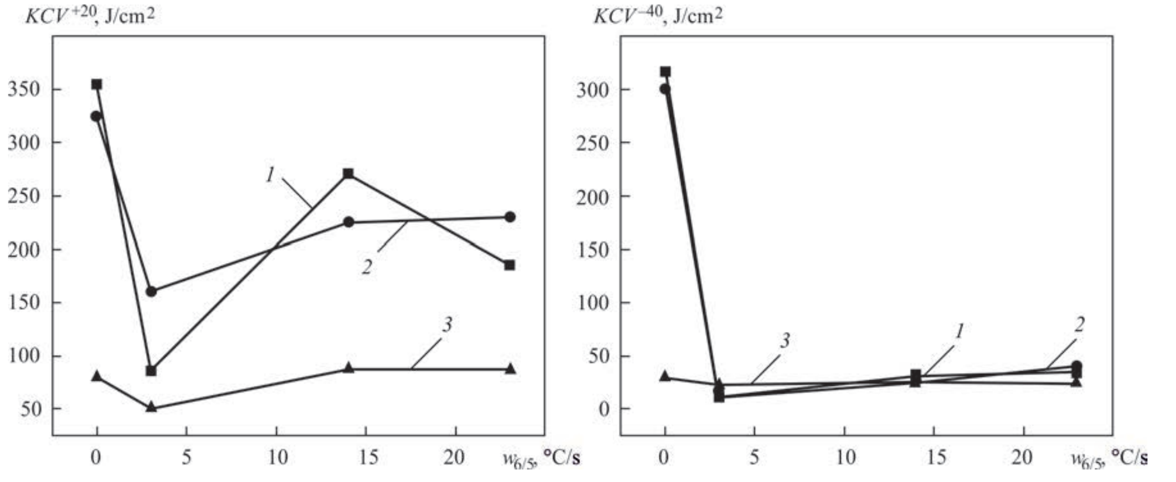

Figure 4. Impact toughness of the investigated steels depending on the value of cooling rate $w_{6/5}$: *1* — 06G2BDP; *2* — 06G2B; *3* — 10KhSND

in the cooling rate $w_{6/5}$ to 14 °C/s leads to a decrease in the average grain size to 100 μm, an increase in the specific share of upper bainite to 70 % and, as a consequence, to an increase in the values of static strength. However, the values of cold resistance (impact toughness at negative temperatures) are at the lower limit of admissibility. The latter fact is explained by a high content of upper bainite (30 %) in the produced structure.

Thus, taking into account the data obtained from the tests for corrosion resistance, steel 06G2BDP has higher characterisitcs than other investigated steels. Considering also that as to the values of static strength, ductility and toughness, steel 06G2BDP is not inferior to steel 06G2B and is superior to steel 10KhSND, its use is appropriate as an alternative to the mentioned steels in the manufacture of modern metal structures by gas-shielded manual arc and mechanized welding in the range of cooling rates of the HAZ metal typical to them.

Conclusions

The carried out investigations of the impact of thermal welding cycles on the structure and properties of steel 06G2BDP showed the following:

● at the cooling rate of the simulated HAZ metal $w_{6/5}$ = 3 °C/s (typical for submerged-arc welding processes), it is observed that the yield strength significantly decreases to 490 MPa and impact toughness drops to the values that do not meet the requirements of EuroNorm standards (less than 34 J/cm^2), which is predetermined by a significant increase in the grain size of the structure produced under such cooling conditions;

● it is possible to increase the value of static strength and impact toughness by the growth of the minimum cooling rate of the simulated HAZ metal $w_{6/5}$ to 14 °C/s. In this case, a structure with a grain size of about 100 μm is formed in the HAZ metal.

It was established that the optimal combination of the mechanical properties and structure can be achieved at the cooling rate of the HAZ metal of welded joints $w_{6/5}$ in the range from 14 to 23 °C/s.

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