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STRUCTURE AND PROPERTIES OF WELDED JOINTS OF 06G2BDP STEEL

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ABSTRACT

Ensuring reliable operation of bridge metal structures requires solving a wide range of issues, in particular, development of new local materials with guaranteed characteristics, which would provide the required durability of bridge structures. Modern requirements to materials for building metal structures and bridges are met by high-strength sparsely-alloyed 06GB, 06G2B steels, which were the base for development of 06G2BDP steel of 355–500 MPa class with higher resistance to atmospheric corrosion. Application of the corrosion-resistant steel for fabrication of bridge metal structures will allow improvement of their reliability and service life. The work deals with the influence of welding technology parameters on the structure and properties of welded joints of 06G2BDP steel.

KEYWORDS: bridge metal structures, corrosion-resistant steel, structure, welded joints, welding consumables, mechanical properties

INTRODUCTION

At present there is the need in metal structure fabrication for high-strength sheet steels with high mechanical properties and increased resistance to atmospheric corrosion [1–3]. This is indicated by the results of inspection of such metal structures with concrete roadway, main girders and transverse beams of steel. They showed that the main type of their damage is reduction of the cross-section of the girths and webs of the beams as a result of corrosion, which significantly lowers the structure load-carrying capacity and bridge serviceability [4–7]. A combination of design and technology factors, as well as application of ordinary construction steels in earlier build bridges, having relatively low corrosion resistance, promote an accelerated development of this process [8]. Application of higher corrosion resistance steels in metal span structures of bridges is important in terms of extension of their service life and lowering the bridge operating costs.

At present sparsely-alloyed steels of 06GB, 06G2B grades have been introduced into construction of critical welded metal structures [9]. These steels have a higher strength and cold resistance and by these values they differ favourably from 09G2S, 10KhSND steels, which are usually applied in fabrication of local metal structures. At the same time, in order to increase the corrosion resistance of 06G2B steel, a new steel of 06G2BDP grade was developed on its base [10], which contains 0.04–0.12 % carbon, depending on the steel grade, 0.90–1.75 % manganese, 0.30–0.45 % copper, and ≤0.012 % sulphur. Higher phosphorus content, particularly in contact with copper, enables increasing the corrosion resistance, but it can impair the deformation properties of the metal and can cause its cold brittleness, so that phosphorus content in the steel is limited to 0.05 % (Table 1). A combination of high strength and high impact toughness of 06G2BDP steel (Table 2) was produced by modifying treatment and thermal improvement.

Table 1. Chemical composition of the studied steels, wt.%

Rolled stock/melt	Thickness, mm	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	Nb	Ti
06G2BDP experimental melt	13	0.068	1.36	0.082	0.053	0.011	0.30	0.14	0.15	0.47	0.018	0.056	0.004
06G2BDP TU U27-05416823-078:2006	8–50	0.04–0.08	1.10–1.40	0.15–0.35	0.030–0.050	0.012	Before 0.30	Before 0.30	0.02–0.05	0.30–0.45	0.02–0.05	0.010–0.030	Before 0.020
06G2B	–	0.08	1.3	0.25	0.025	0.01	–	–	0.1	0.3	0.02	–	–
10KhSND	–	≤0.12	0.8	0.8	0.03	0.035	0.6	0.5	–	0.4	–	–	–

Table 2. Mechanical properties of steels

Steel grade/class	σ_y, MPa	σ_t, MPa	δ_5, %	KCV^{-20}	KCV^{-40}
06G2B C390	390	490	22	–	98
06G2BDP C390	390	490	22	68	49
10KhSND C390	390	530–685	19	–	29
06G2BDP experimental melt	529–534	645–666	24.7–27.3	298–310	230–298

By the results of studying the static strength, ductility, impact toughness and corrosion resistance it is shown that 06G2BDP steel is promising in terms of its application for building bridges, and other critical structures [11].

INVESTIGATION PROCEDURE

In order to ensure reliable operation of the structure, the welded joint metal, including the weld and HAZ, should have sufficient strength and cold resistance. These characteristics are determined, on the one hand, by the chemical composition, heat treatment and thickness of the metal being welded, and on the other hand, by welding conditions: heat input, preheating, technique of making the joints, etc. The work is devoted exactly to this analysis.

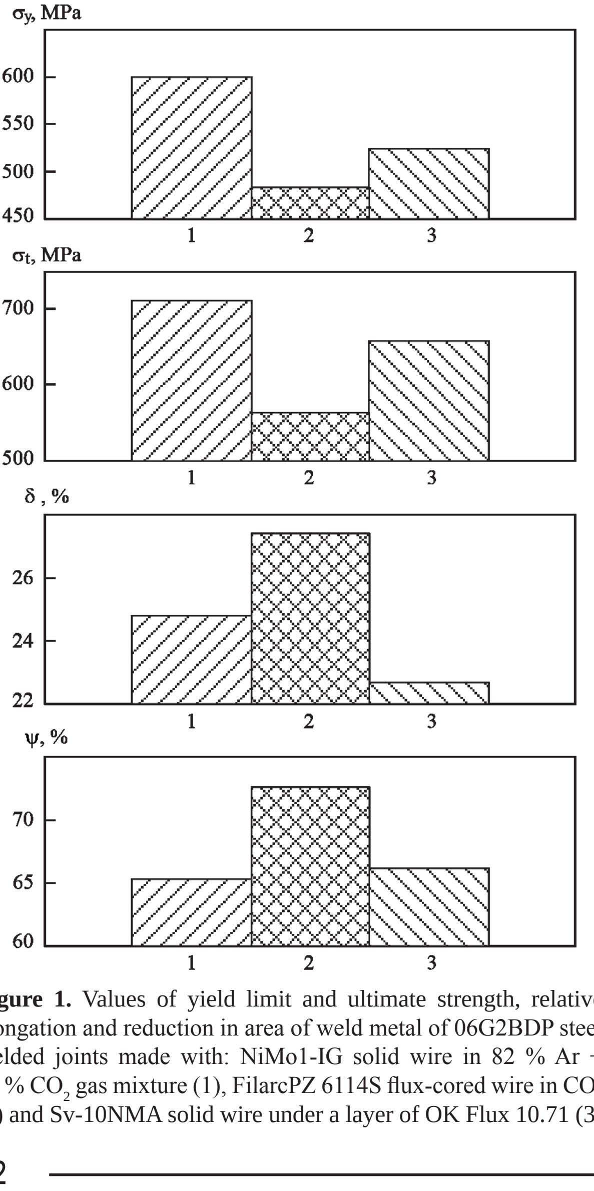

Figure 1. Values of yield limit and ultimate strength, relative elongation and reduction in area of weld metal of 06G2BDP steel welded joints made with: NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 gas mixture (1), FilarcPZ 6114S flux-cored wire in CO_2 (2) and Sv-10NMA solid wire under a layer of OK Flux 10.71 (3)

For further development of arc welding technologies for fabrication of metal structures of bridge spans and engineering facilities from 06G2BDP steel, investigations were conducted using modern methods of light and electron metallography, and physical tests to study the influence of arc welding technologies on structure formation, mechanical properties and cold resistance of the HAZ metal. Flux-cored wire and solid wire for mechanized gas-shielded welding and solid wire for automatic submerged-arc welding were selected for these purposes.

Butt joints with V-shaped groove were made from 13 mm 06G2BDP steel for investigation performance. Mechanized welding in 82 % Ar + 18 % CO_2 gas mixture was performed with 1.2 mm Ni-Mo1-IG solid wire (Boehler Thyssen Company) and in CO_2 with 1.2 mm Filarc PZ 6114S flux-cored wire (ESAB Company). Welding modes were practically the same for both variants and were as follows: I_w = 190–220 A, U_a = 26–28 V, V_w = 14–16 m/h, shielding gas (mixture) flow rate was 15–18 l/min. Automatic submerged-arc welding with OK Flux 10.71 ceramic flux (ESAB Company) was performed with 4 mm Sv-10NMA solid wire in the following mode: I_w = 520–530 A, U_a = = 32 V, V_w = 28 m/h.

WORK RESULTS AND THEIR DISCUSSION

Building metal structures are usually made using mechanized gas-shielded and automatic submerged-arc welding. When mounting the structures, welding is most often performed by manual arc process, using coated electrodes.

Many years of experience showed that mechanized gas-shielded arc welding of structural steels of C390 grade is performed with Sv-08G2S solid wire, automatic submerged-arc welding is conducted with AN-348 or AN-47 flux with wires of Sv-08GA or Sv-10NMA grades, and manual arc welding — with electrodes of UONI-13/55 grade.

As regards welding steels of C500 and higher grade, to which 06G2BDP steel belongs, the normative documents on bridge building do not give any precise recommendations on selection of materials for their welding. Therefore, one of the main tasks of this study was substantiation of application of a par-

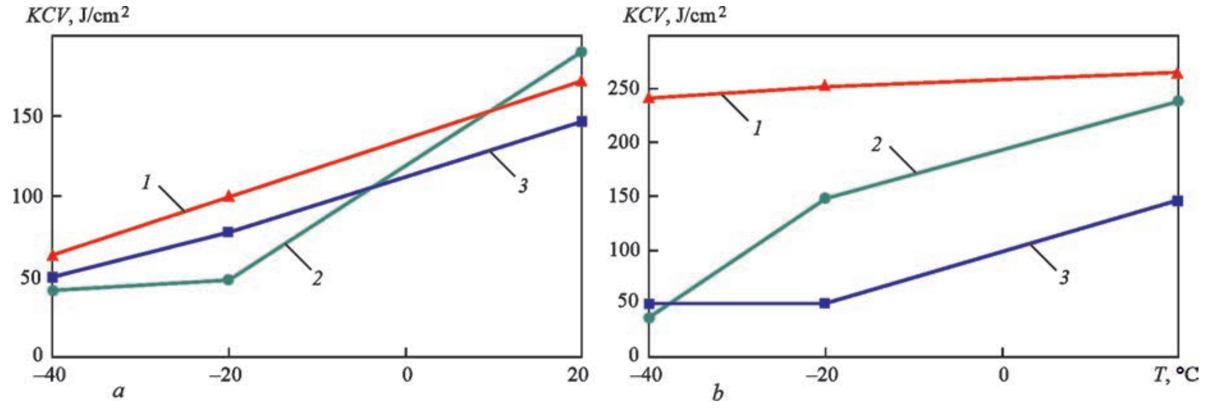

Figure 2. Impact toughness of weld metal (*a*) and HAZ metal (*b*) in 06G2BDP steel welded joints: *1* — NiMo1-IG wire, 82 % Ar + 18 % CO_2; *2* — FilarcPZ 6114S flux-cored wire, CO_2; *3* — Sv-10NMA wire, OK Flux 10.71

ticular material for welding metal of the above class. Obtained data on mechanical properties of the weld metal show (Figure 1) that the values of static strength and ductility of the weld metal, both in mechanized gas-shielded welding and in automatic submerged-arc process, are considerably higher than similar values of base metal of 06G2BDP steel of C390 class.

NiMo1-IG solid wire in combination with a shielding gas mixture of 82 % Ar + 18 % CO_2 and Sv-10NMA solid wire under a layer of OK Flux 10.71 ceramic flux ensure equivalent strength and 15–20 % higher σ_y and σ_t values of base metal of 06G2BDP steel of 500 class. Ductility values are also at a sufficiently high level, exceeding the standard values for steel.

By the static strength and ductility values the recommended welding processes and consumables ensure the required level of weld metal mechanical properties, and they can be used for fabrication of metal structures from 06G2BDP steel of C390 class, and they can be applied for welding steels of C500 class, except for Filarc PZ 6114S flux-cored wire.

Derived results of impact toughness studies (Figure 2) demonstrate that welds made with NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 gas mixture and with Sv-10NMA solid wire under a layer of OK Flux 10.71 correspond to standard values ($KVC^{-20} \geq 68$ J/cm^2 and $KCV^{-40} \geq 49$ J/cm^2). In particular, in welding with NiMo1-IG wire in a gas mixture, *KCV* values of the metal of welds and HAZ exceed the base metal impact toughness 1.5–2.0 and 3.0–3.5 times, respectively.

High values of impact toughness are confirmed by fractographic studies of sample fractures after testing. So, at testing samples with a notch in the weld middle, the fracture mode at –40 °C temperature at the notch tip and in the final fracture zone is ductile with pit size d_p = 0.4–5 μm, being quasibrittle only in the zone of the main crack propagation (Figure 3). At the same temperature conditions in samples with a notch in the HAZ the fracture mode is 100 % ductile in all the zones with a large cluster of small pits of d_p = = 1–5 μm (Figure 4).

Contrarily, application of Filarc PZ 6114S flux-cored wire provides impact toughness of the metal of welds and HAZ of welded joints at the required level only at 20 °C testing temperature. At testing temperature lowering to –20 and –40 °C *KCV* values decrease, and in the weld metal they are even lower than the standard ones.

This is also indicated by the results of fractographic studies at similar temperatures of sample fractures with a notch both in the weld center, and in the HAZ. In the notch tip and in the final fracture zone for –40 °C temperature, a ductile fracture mode is observed in the weld metal with pit size d_p = 0.5–4 μm (Figure 5, *b*), and in the zone of the main crack prop-

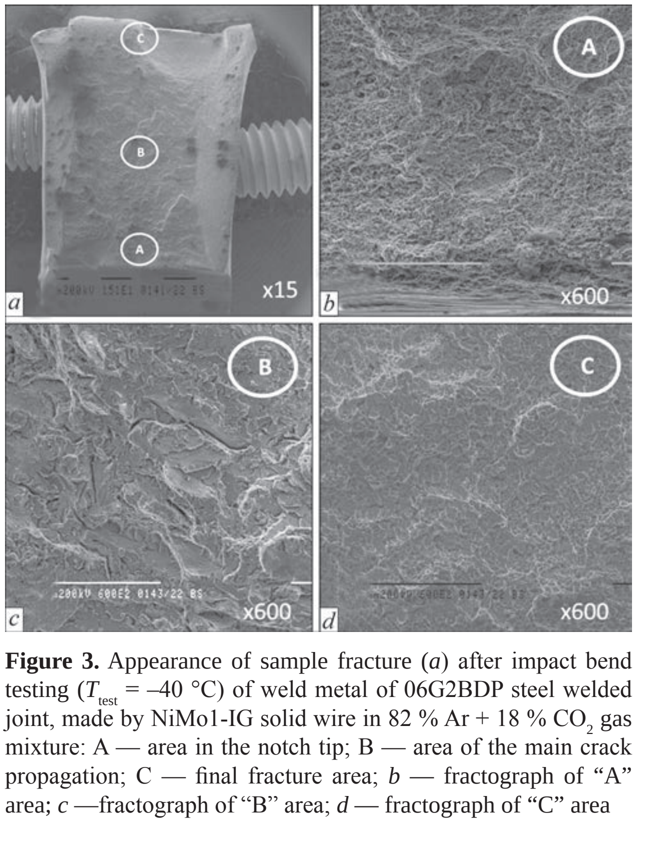

Figure 3. Appearance of sample fracture (*a*) after impact bend testing (T_{test} = –40 °C) of weld metal of 06G2BDP steel welded joint, made by NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 gas mixture: A — area in the notch tip; B — area of the main crack propagation; C — final fracture area; *b* — fractograph of “A” area; *c* —fractograph of “B” area; *d* — fractograph of “C” area

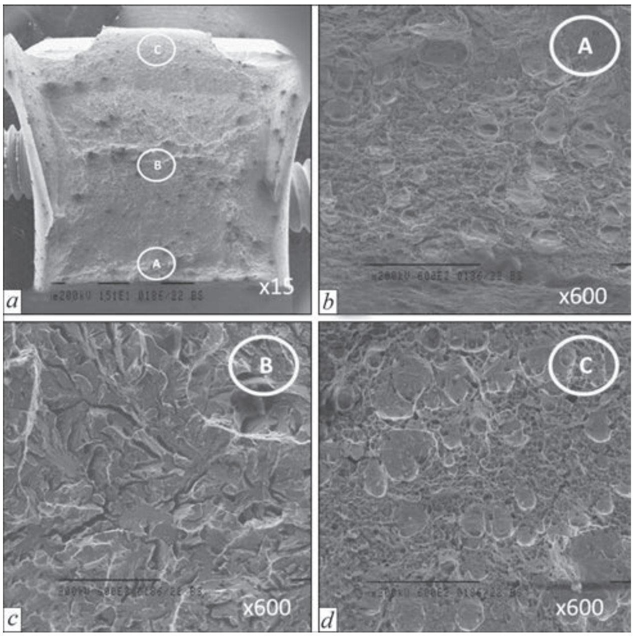

Figure 4. Appearance of sample fracture (*a*) after impact bend testing (T_{test} = –40 °C) of HAZ metal of 06G2BDP steel welded joint, made by NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 gas mixture: A — area in the notch tip; B — area of the main crack propagation; C — final fracture area; *b* – fractograph of “A” area; *c* — fractograph of “B” area; *d* — fractograph of “C” area

agation brittle fracture prevails with cleavage facet diameter of 10–55 μm. Approximately the same situation is characteristic for fracture of samples with a notch in the HAZ at –20 °C testing temperature. At the same time, at temperature lowering to –40 °C, the quasibrittle and brittle fracture modes are observed at the notch tip and in the zone of the main crack propagation with cleavage facet size d_f = 8–30 μm (Figure 6, *c*). The fracture mode is ductile with small pit size d_p = 1–10 μm only in the final fracture zone (Figure 6, *d*).

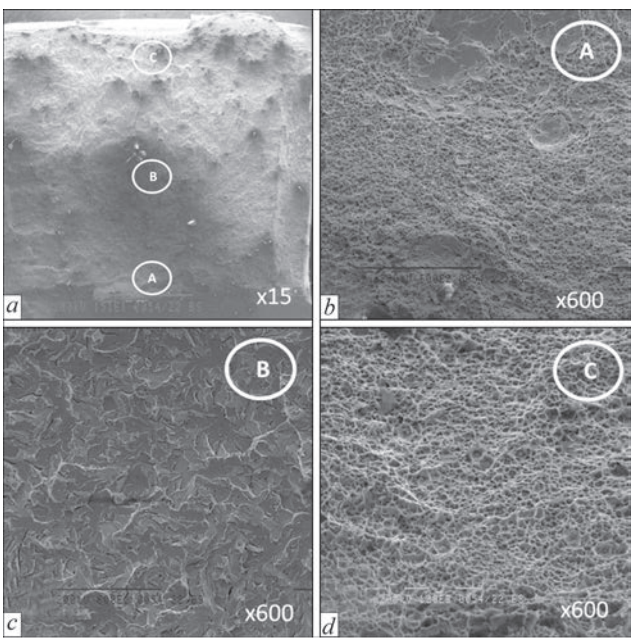

Figure 5. Structure of the weld upper layer in welding with stationary arc (*a*, *b*), in PAW (*c*, *d*) and in welding with pulsating arc (*d*, *e*): *a*, *c*, *e* — optical microscopy at ×500 (reduced 2 times); *b*, *d* — SEM

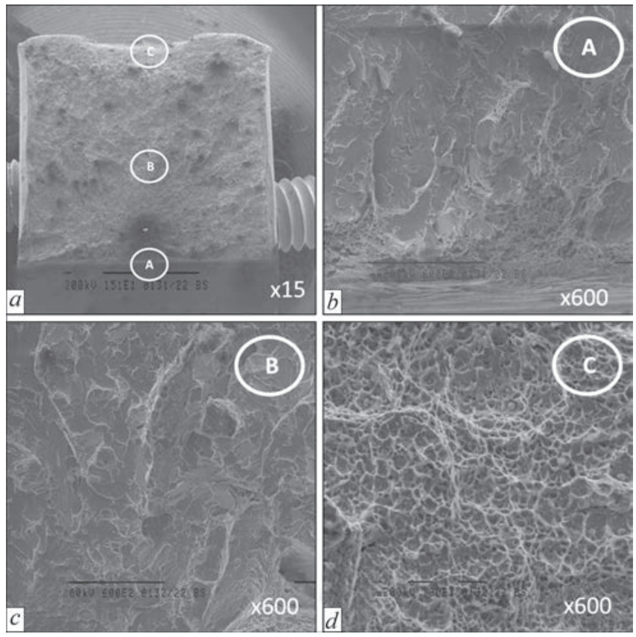

Figure 6. Macrosections of Tekken samples of 13KhGMRB steel joints made by PAW: *a* — without preheating; *b* — PT = 120 °C

By the results of fractographic investigations it was found that for all the studied variants of welding at low temperatures the HAZ metal ductility is somewhat higher than that of weld metal, which is ensured by dispersion of the structural components. Maximal values of impact toughness at all the testing temperatures are characteristic for 06G2BDP steel welded joints, made by mechanized welding with NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 mixture.

Change of the values of mechanical properties and impact toughness is associated with structural transformations in the welded joint zones, both in the weld metal and in the HAZ metal.

At mechanized solid wire welding the most highly dispersed structure forms in the weld metal which consists of ferrite-carbide mixture with sparse hardly noticeable thin precipitates of hypoeutectoid ferrite along the primary grain boundaries of higher hardness of 2200 MPa (Figure 7, *a*). In the overheated subzone of the HAZ a fine structure of acicular ferrite forms with incomplete precipitation of hypoeutetoid ferrite. Hardness value of this zone is equal to 2500 MPa (Figure 7, *b*).

At mechanized flux-cored wire welding the weld metal forms a microstructure of acicular ferrite with a large fraction of coarse plates of hypoeutectoid ferrite, which precipitated from equidirectional coarse elongated ferrite grains of 2110 MPa microhardness, growing into the bulk (Figure 8, *a*). The HAZ metal forms a fine ferritic structure with hardness increase

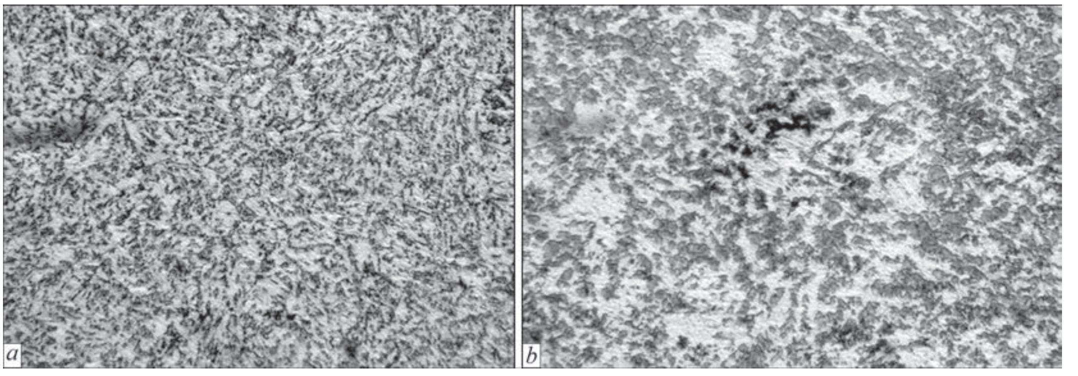

Figure 7. Microstructure (×500) of 06G2BDP steel welded joint made with NiMo1-IG solid wire in 82 % Ar + 18 % CO_2 gas mixture: *a* — weld; *b* — HAZ

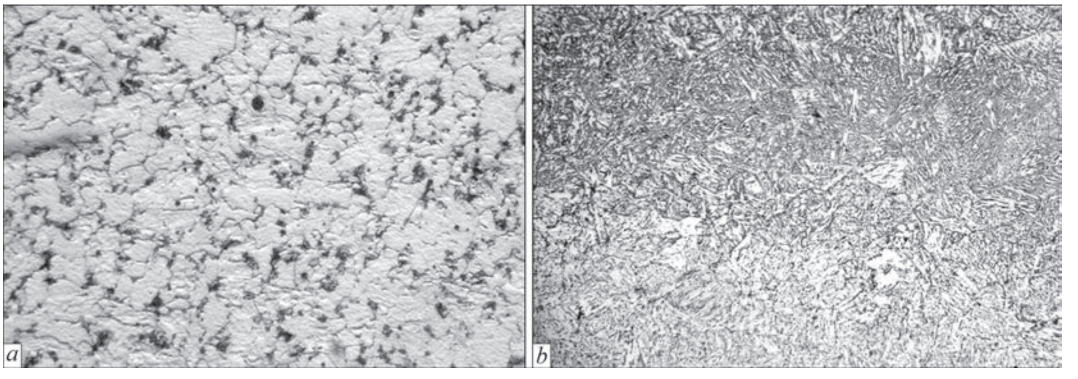

Figure 8. Microstructure (×500) of 06G2BDP steel welded joint made with FilarcPZ 6114S flux-cored wire in CO_2: *a* — weld; *b* — HAZ

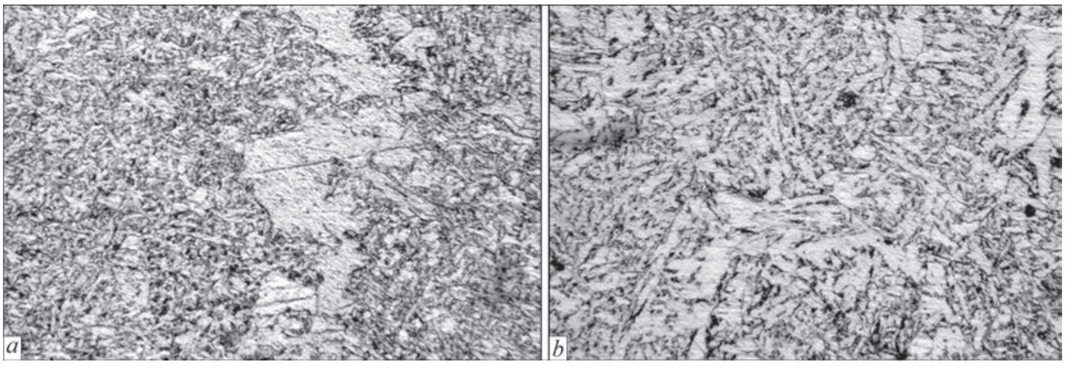

Figure 9. Microstructure (×500) of 06G2BDP steel welded joint made with Sv-10NMA solid wire under a layer of OK Flux 10.71: *a* — weld; *b* — HAZ

up to 2450 MPa in the overheated subzone and hardness lowering to 2100 MPa in the incomplete recrystallization subzone (Figure 8, *b*).

At automatic submerged-arc welding the weld metal develops an acicular ferritic structure with the most ramified network of pronounced hypoeutectoid ferrite along the boundaries of ferrite grains of a more round shape. Weld metal structure has the lowest microhardness of 2080 MPa. The fusion zone hardness is 2000 MPa (Figure 9, *a*). In the HAZ overheated subzone an acicular ferritic structure forms with coarse plates of hypoeutectoid ferrite and Widmanstaetten ferrite areas of 2050–2080 MPa hardness (Figure 9, *b*).

In addition, at automatic submerged-arc welding a tempered area of 6 mm width develops in the welded joint at 5 mm distance from the fusion line with a considerable hardness lowering to 1600–1800 MPa, and with emergence of a fine-grained ferritic-pearlitic structure.

In terms of formation of a dispersed ferritic-carbide structure and achieving high impact toughness values, the most favourable of the above-mentioned combinations of welding consumables is application of NiMo1-IG solid wire of Boehler Company at mechanized welding of 06G2BDP steel in 82 % Ar + 18 % CO_2 gas mixture.

CONCLUSIONS

Investigations of the influence of mechanized gas-shielded arc and automatic submerged-arc welding on the mechanical properties and structure of welded joints of 06G2BDP steel revealed the following:

● by the values of static strength and ductility the above-mentioned welding processes and welding consumables, namely NiMo1-IG solid wire in combination with 82 % Ar + 18 % CO_2 gas mixture, Filarc PZ 6114S flux-cored wire with CO_2 and Sv-10NMA solid wire in combination with OK Flux 10.71 provide the required level of weld metal mechanical properties, and they can be used for fabrication of metal structures from rolled stock of 06G2BDP steel of C390 class;

● on the other hand, the above-mentioned combinations of welding consumables, except for Filarc PZ 6114S flux-cored wire in CO_2, can be used for welding metal structures from 06G2BDP of C500 grade;

● metallographic investigations of microstructure of all the welded joint zones and fractographic studies of the sample fracture surfaces after impact bend testing showed that from the above-mentioned combinations of welding consumables application of NiMo1-IG solid wire of Boehler Company at mechanized welding in 82 % Ar + 18 % CO_2 gas mixture can be the most favourable in terms of formation of a dispersed ferritic-carbide structure and achieving high impact toughness values;

● application of the technology of automatic submerged-arc welding is rational at fabrication of metal structures, which will operate at temperatures not lower than –20 °C, and for products welded with flux-cored wire in CO_2 the working temperature range should only be positive (not lower than plus 20 °C), from the viewpoint of achieving impact toughness values higher than the standard values.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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