WELDABILITY OF SPARSELY-ALLOYED STEELS 06GBD AND 06G2B

V.D. POZNYAKOV, S.L. ZHDANOV, A.A. MAKSIMENKO, A.G. SINEOK and **A.M. GERASIMENKO**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

The aim of this work was the investigation of weldability of sparsely-alloyed niobium-containing steels 06GBD and 06G2B with the yield strength of more than 390 MPa, and also evaluation of properties of their welded joints at different technological welding processes as-applied to manufacture of unique building structures (bridges, tanks of 50,000–70,000 m^3 capacity, blast furnaces). Basing on the analysis of thermokinetic diagram obtained using rapid-response dilatometer and results of tests of model thermocycled specimens the correlation at the cooling rates $w_{6/5}$ in the range of 1.3–70 °C/s between structure of metal of heat-affected zone of welded joints and their properties was established. Considering the results of tests on delayed fracture of welded joints, the range of admitted energy inputs of welding was established providing their high cold resistance and resistance to cold crack formation. The offered welding conditions and welding consumables found their application in manufacture of steels 06GBD and 06G2B welded structures of oil tanks of large capacity and bridges. 8 Ref., 5 Tables, 8 Figures.

Keywords: *sparsely-alloyed steel, weldability, thermokinetic diagram, cooling rate, structure, simulated metal of heat-affected zone, cold cracks, technological sample*

The rational application of modern sparsely-alloyed materials with high values of mechanical properties (more than 390 MPa) allows effective decreasing of metal intensity and increasing of reliability and service life of metal structures for machine building and construction. The used steels contain limited amount (up to 0.09 wt.%) of carbon, manganese and niobium. To achieve the required complex of their mechanical properties, both heat and also heat-mechanical treatment (controlled rolling) are used. In special cases, to increase corrosion resistance the copper is added into these steels in the amount of up to 0.3 wt.%.

The indisputable advantages of sparsely-alloyed steels, as compared to those known materials as steels 09G2S and 10KhSND, are their high cold resistance and good weldability [1–3]. Meantime it is known that in the process of manufacture of welded metal structures the resistance of welded joints to delayed and brittle fractures can decrease.

The aim of this work was the detailed evaluation of weldability of sparsely-alloyed niobium-contained steels 06GBD and 06G2B with yield strength of $\sigma_y \geq 390$ MPa and also investigation of properties of their welded joints at different technological processes as-applied to manufacture of unique building structures of different purpose (bridges, tanks of 50,000–70,000 m^3 capacity, blast furnaces).

The steels of grades 06GBD and 06G2B (TU U 27.1-05416923-085:2006) were developed by the Mariupol Research Institute of Structural Materials «Prometey» and are supplied of 8–50 mm thickness. By variation of modes of heat treatment and alloying, the obtaining of four levels of strength properties $\sigma_y \geq 355$, 390, 440 and 490 MPa [4–6] is controlled. The requirements to chemical composition and properties according to the technical specifications are given in Tables 1 and 2. During present investigations the steels 06GBD (class of strength C390) and 06G2B (class of strength C440) were used. The investigations carried out earlier at the E.O. Paton Electric Welding Institute prove the sufficiently high resistance of these steels to laminar and laminar-brittle fracture in the direction of the axis z [4]. According to carbon equivalent they can be referred to the class of a good weldability (C_{eq} = 0.33–0.43). However this characteristic is approximate, therefore, the additional investigations were required for final decision about fitness of these steels to welding.

To study structural transformations in HAZ metal of steel 06GBD under the effect of thermal cycles of welding the quick-response dilatometer of complex Gleeble-3800 [7] was used, where cylindrical specimens of 6 mm diameter and 86 mm length were heated up to the temperature of 1200 °C at the speed of 150 °C/s and then

© V.D. POZNYAKOV, S.L. ZHDANOV, A.A. MAKSIMENKO, A.G. SINEOK and A.M. GERASIMENKO, 2013

Table 1. Chemical composition of steels 06GBD and 06G2B, wt.%, not more than

Grade of steel, strength class	C	Si	Mn	Nb	V
06GBD, C355	0.04–0.08	0.15–0.35	0.9–1.2	0.01–0.03	0.02–0.04
06GBD, C390	0.04–0.08	0.25–0.50	1.1–1.4	0.01–0.03	0.02–0.05
06G2B, C440	0.04–0.08	0.25–0.50	1.3–1.6	0.03–0.05	0.03–0.07
06G2B, C490	0.05–0.09	0.25–0.50	1.5–1.7	0.03–0.05	0.04–0.07

Table 1 (cont.)

Grade of steel, strength class	Mo	Ti	Cr	Ni	Cu	S	P
06GBD, C355	0.05	0.02	0.2	0.3	0.3	0.01	0.025
06GBD, C390	0.08	0.02	0.2	0.3	0.3	0.01	0.025
06G2B, C440	0.10	0.02	0.2	0.3	0.3	0.01	0.025
06G2B, C490	0.12	0.025	0.2	0.3	0.3	0.01	0.025

Table 2. Mechanical properties of steels 06GBD and 06G2B

Grade of steel, strength class	σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	ψ_z, %	KCV, J/cm^2, at T_{test}, °C		
						−40	−60	−70
	Not less than							
06GBD, C355	355	450	22	55	25	98	78	59
06GBD, C390	390	490	22	55	25	98	78	59
06G2B, C440	440	540	22	55	25	98	78	59
06G2B, C490	490	590	20	55	25	98	78	59

cooled in the temperature range of 600–500 °C at different rates (1.3–70 °C/s).

The analysis of thermokinetic diagram (Figure 1) and microstructures of simulated HAZ metal, cooled at different rates, proves that in the whole investigated range (1.3–70 °C/s) the ferrite-pearlite structure at the overheat area is observed (Figure 2). At $w_{6/5} \geq 27$ °C/s the precipitations of MAC-phase appear, the percentage correlation of which is increased from 1.20 to 5.72 % at the increase of cooling rate to $w_{6/5} =$ = 70 °C/s. Here both its hardness is increased from HV 140 to HV 171 as well as number of grains from 5 to 8–9.

In spite of similarity of structures (Figure 2, *b*–*d*) some distinctions on the shape of pearlite component are observed in them. Thus, at $w_{6/5} =$ = 10.1 °C/s thin pearlite plates (Figure 2, *b*) are observed in the structure along the boundaries of ferrite grains. With increase of cooling rate up to $w_{6/5} = 27$ °C/s the plates of pearlite are refined and multiplied. Besides, separate uniaxial grains of pearlite appear (Figure 2, *c*). At the maximum cooling rate in the investigated range $w_{6/5} = 70$ °C/s the structure is enlarged, the large pearlite colonies are appeared along with the plate precipitations of pearlite along the boundaries of pearlite grains (Figure 2, *d*).

The evaluation of mechanical properties and resistance of welded joints to brittle fracture were carried out according to the methods described in [8]. The tensile and bending tests were applied to the specimens of the sizes of 150 × 12 × 12 mm, which were cut out of the semi-products of steel 06GBD and subjected to the effect of thermal

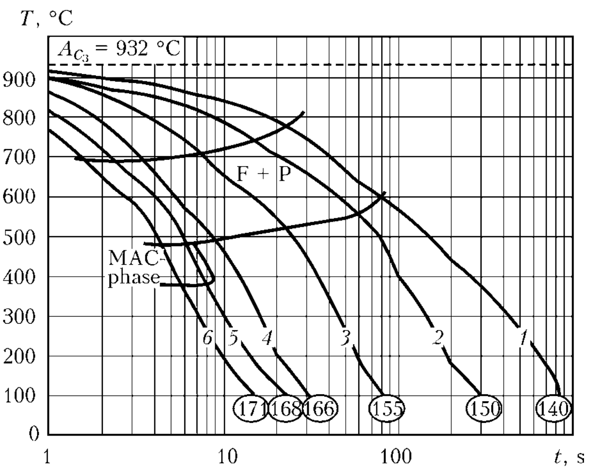


Figure 1. Thermokinetic diagram of transformation of austenite for steel 06GBD at different cooling rate $w_{6/5}$ = 1.3 (*1*), 3.1 (*2*), 10.1 (*3*), 27 (*4*), 56.7 (*5*) and 70 (*6*) °C/s

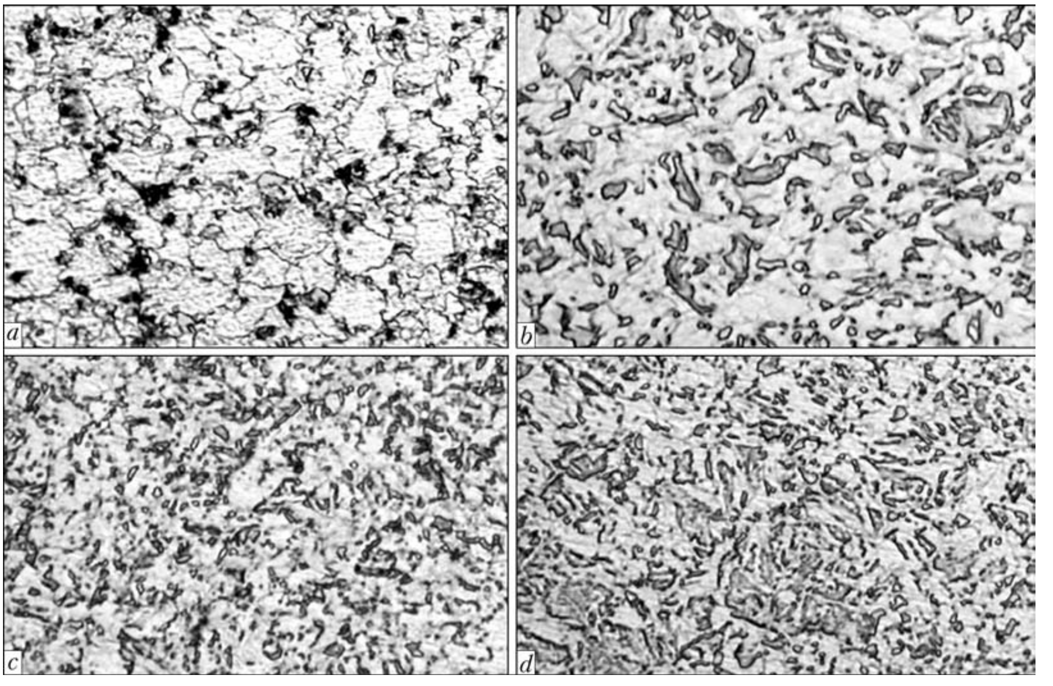


Figure 2. Microstructures (×500) of steel 06GBD specimens at $w_{6/5}$ = 1.3 (*a*), 10.1 (*b*), 27 (*c*) and 70 (*d*) °C/s

cycles of welding (heating up to 1250 °C at the speed of 150 °C/s and cooling at different rates within the range of 1.5–25 °C/s). The chemical composition of investigated rolled metal of different thicknesses δ is given in Table 3, and results of mechanical tests of the simulated HAZ metal of the investigated steel are given in Figures 3–5.

The analysis of data obtained as a result of rupture tests of specimens (see Table 3 and Figure 3, *a*, *b*) showed that with decrease of cooling rate the values σ_y and σ_t characterizing strength of metal are monotonously decreased. Values of yield strength are most intensively decreased. According to the results of mechanical tests, in the range $w_{6/5}$ = 1.5–3 °C/s the weakening of HAZ metal occurs, characterized by 25–60 MPa decrease of the values of yield strength of HAZ metal as compared to the initial data (Figure 3, *a*). At such cooling rates the HAZ metal has σ_y values lower than values established in the standard documents on steel. Meantime the tensile strength of HAZ metal in the whole investigated range of cooling rates did not decrease lower than values specified by technical specifications on steel.

The ductile properties of HAZ metal are at the high level. In spite of some negligible decrease of values of elongation with increase of cooling rate they exceed 22 % (see Figure 4, *a*). At the same time the values respectively to the reduction in area practically did not change (Figure 4, *b*).

With the decrease of cooling rate the impact toughness of HAZ metal is decreased independently of test temperature. However at 20 °C the value $KCV_{+20} \geq 170$ J/cm^2 (see Figure 5, *a*) remains considerably high in the whole range. The negative influence of cooling rate was revealed during the tests of specimens under the conditions of lowered temperatures. If for the thicknesses of 12 and 14 mm the higher values are characteristic at $w_{6/5} \geq 10$ °C/s (Figure 5, *b*), then at $w_{6/5}$ = 1.5–10 °C/s the sharp decrease of values of impact toughness (KCV_{-40} = 18–24 J/cm^2) is observed.

It was established that the required complex of mechanical properties of HAZ metal can be provided in welding at limited heat inputs when

Table 3. Chemical composition of investigated rolled metal of steel 06GBD, wt.%

δ, mm	C	Mn	Si	P	S	Cr	Mo	Cu	Nb	V
12	0.066	1.20	0.20	0.008	0.006	0.14	0.13	0.22	0.019	0.04
14	0.069	1.22	0.18	0.009	0.008	0.13	0.12	0.21	0.021	0.05
20	0.066	1.23	0.19	0.010	0.009	0.22	0.13	0.22	0.021	0.05
32	0.064	1.24	0.17	0.011	0.011	0.23	0.10	0.20	0.020	0.05
40	0.070	1.22	0.17	0.018	0.010	0.21	0.12	0.21	0.019	0.05

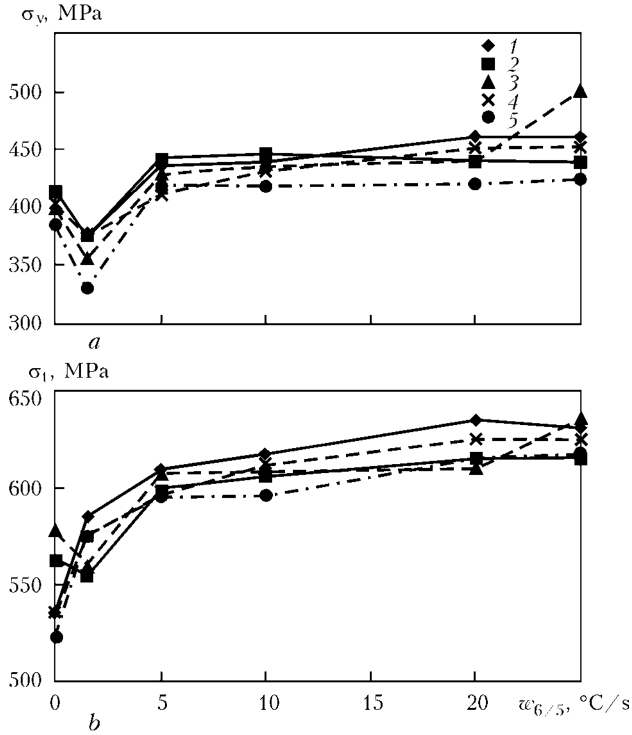


Figure 3. Dependence of yield strength (*a*) and tensile strength (*b*) of steel 06GBD on cooling rate of HAZ metal at different thickness δ = 12 (*1*), 14 (*2*), 20 (*3*), 32 (*4*) and 40 (*5*) mm

minimal cooling rates of welded joints do not drop lower than 10 °C/s.

The resistance of welded joints to formation of cold cracks was evaluated according to the results of tests of Implant and Tekken specimens and technological butt samples «rigid contour welding». To conduct tests according to the Implant method the cylindrical specimens-inserts of 6 mm diameter with screw notch were used manufactured of roll metal of steels 06GBD and 06G2B of different thickness. The cooling rate of HAZ metal of the Implant specimens (in the range of 5–80 °C/s) was adjusted changing the energy input of welding and elongation of binding beads. The content of diffusive hydrogen $[H]_{diff}$ in the metal deposited using electrodes UONI-13/55 (during determination by chromatographic method) was measured from 5 to 15 ml/100 g. The axial static loading of specimens-inserts was applied after welding and their cooling down to the temperatures of 100–150 °C. The maximal tensile stress from the outer loading σ_{cr}, at which no cracks are formed during 20 h in Implant specimens, was accepted as the criterion for resistance of HAZ metal to delayed fracture.

As a results, it was established that σ_{cr} of steel 06G2B Implant specimens 30 mm thick at the cooling rates, characteristic for welding modes without preheating ($w_{6/5} \leq$ 25 °C/s), and

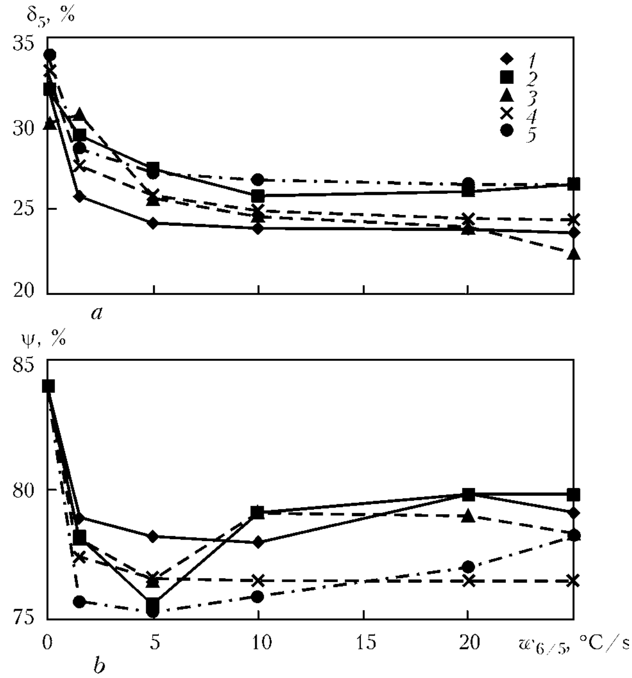


Figure 4. Dependence of relative values of elongation (*a*) and reduction in area (*b*) of HAZ metal of steel 06GBD on cooling rate of metal of different thickness δ = 12 (*1*), 14 (*2*), 20 (*3*), 32 (*4*) and 40 (*5*) mm

$[H]_{diff} \leq$ 10 ml/100 g are at the high level ($\sigma_{cr} \geq$ $\geq 0.8\sigma_y$ of the base metal).

This proves that probability of cold crack formation in HAZ metal of welded joints of the investigated steels is low. However, when the welding modes are not favorable, the cold cracks

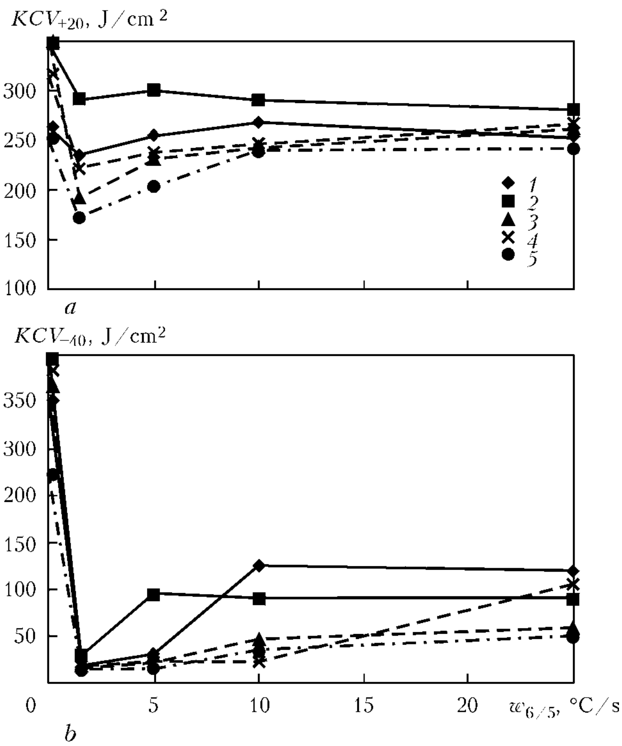


Figure 5. Dependence of impact toughness *KCV* for T_{test} = = +20 (*a*) and –40 (*b*) °C of steel 06GBD HAZ metal on cooling rate at different thickness of rolled metal δ = 12 (*1*), 14 (*2*), 20 (*3*), 32 (*4*) and 40 (*5*) mm

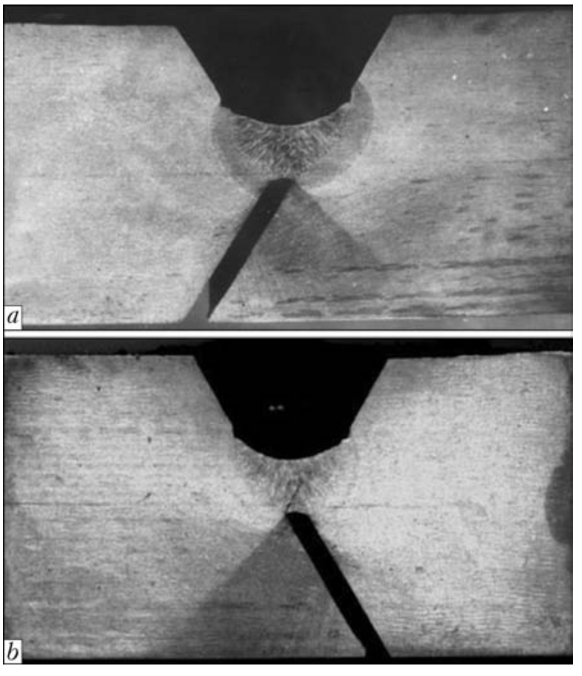


Figure 6. Sections of Tekken samples produced using electrodes UONI-13/55 at $[H]_{diff}$ = 10 (*a*) and 15 (*b*) ml/100 g

can be formed in the weld metal. Thus, at the increase of cooling rate of welded joints up to 60–80 °C/s, characteristic of welding under the conditions of low climatic temperatures, and increase of $[H]_{diff}$ content up to 15 ml/100 g it is possible to prevent the cracks formation having applied the preheating up to 60–90 °C. It is comparable with the data obtained while testing the Tekken samples of steel 06G2B.

It was established that at content of diffusive hydrogen in weld metal not exceeding 10 ml/100 g, the welded joints of steel 06G2B have a good resistance to delayed fracture. Cracks in the Tekken samples are absent (Figure 6, *a*). At higher concentrations of $[H]_{diff}$ the probability of cold cracks formation in welded joints is extremely high, which is evidenced of the test results of Tekken samples, produced using electrodes UONI-13/55 with high content of diffusive hydrogen ($[H]_{diff} \approx$ 15 ml/100 g). Under such welding conditions the cracks in the samples are originated already directly after completion of producing the root bead (during 3–5 min after completion of welding). The process of crack propagation occurs also intensively. Within 5–10 min after formation it was detected at the surface of weld in its end part, and within 2 h after completion of welding it affected the whole its section. The crack originated and propagated exclusively along the weld metal (Figure 6, *b*). It is indirectly proved by the earlier obtained results of tests of Implant specimens, which evidence of high resistance to delayed fracture of HAZ metal of steel 06G2B.

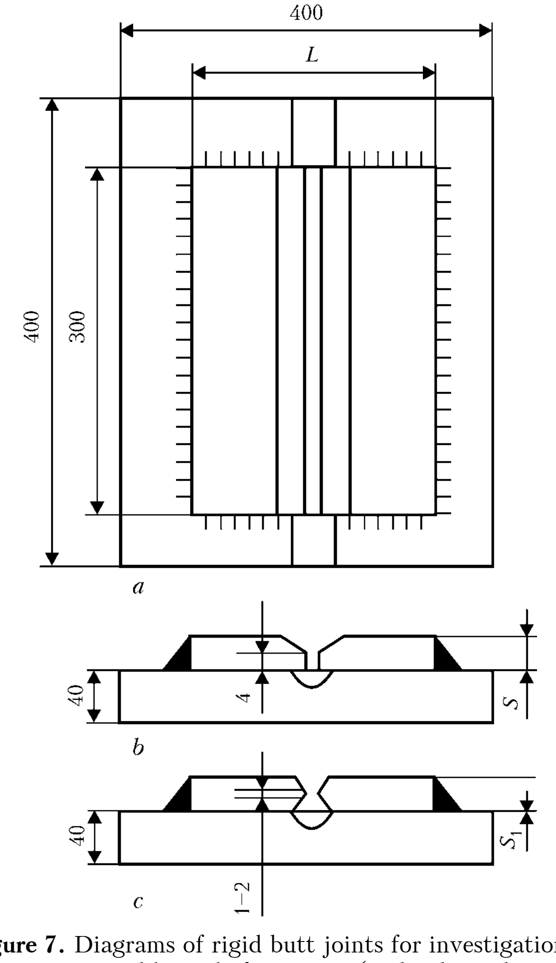


Figure 7. Diagrams of rigid butt joints for investigation of resistance to cold crack formation (technological sample «rigid contour welding»)

The resistance of multilayer welded joints of steel 06GBD to cold cracks formation was evaluated according to the results of tests of technological samples «rigid contour welding» (Figure 7, *a*). The sample represents a massive plate of 400 × 400 × 40 mm size, on which the butt joints of thickness S = 12, 14 and 20 mm with V- (Figure 7, *b*) and X-shaped edges preparation (Figure 7, *c*) for the thicknesses S_1 = 12, 14, 20, 32 and 40 mm, were mounted and welded-on around the whole perimeter. In the samples the obligatory gap of 1.5–2.0 mm is provided, which serves as a concentrator of stresses in welding of joints with 2–4 mm root face to provide technological lack of penetration.

The samples of the width L = 300, 200 and 100 mm were welded at different temperatures and welding modes, meantime controlling the thermal effect using heat source, namely, rate and time of cooling. The rigidity of technological sample was controlled changing the width of plates to be welded.

As the criterion for tendency to delayed fracture the presence/absence of cracks in weld and HAZ metal is served.

The mechanized welding of rigid butt joints of the specimens of steel 06GBD of 100 mm width and thickness of 12, 14 and 20 mm with V- and X-shaped edge preparation were performed in the shielding gas mixture of Ar + 18 % CO_2 using wire Sv-08G2S of 1.2 mm diameter under the conditions of I_w = 180–200 A, U_a = 24–26 V and v_w = 10–12 m/h. The automatic welding of rigid butt joints of specimens 20, 32 and 40 mm thick with X-shaped edges preparation was performed by wire Sv-10NMA of 4 mm diameter under the flux AN-22 at I_w = 500–550 A, U_a = 32–34 V and v_w = 22–26 m/h (root beads). The same conditions were applied also for the next welding of specimens 20 mm thick. The welded joints of steels of 32 and 40 mm thickness were further welded using the more powerful conditions: I_w = = 550–600 A, U_a = 32–34 V, v_w = 20–22 m/h and I_w = 700–750 A, U_a = 32–34 V, v_w = 24–26 m/h, respectively.

The process of cracks initiation and propagation in the samples was controlled by the method of acoustic emission using the device IKD 128. For this purpose the special sensors were mounted on the specimen directly after welding. After welding all samples were subjected to holding for not less than 48 h. Then, they were inspected visually (using magnifying glass with five-fold magnification) to determine the presence/absence of cracks at the surface of welded joint. At the final stage of testing the samples «rigid contour welding», the macrosections were manufactured and examined under the microscope Neophot-2 at ten-fold magnification.

The obtained results evidence also of sufficiently high resistance of welded joints of steel 06GBD to delayed fracture. Even at maximal rigidity of samples (the specimens of 100 mm width) the cold cracks were not revealed in macrosections in mechanized welding in mixture of gases, as well as in automatic submerged arc welding (Figure 8).

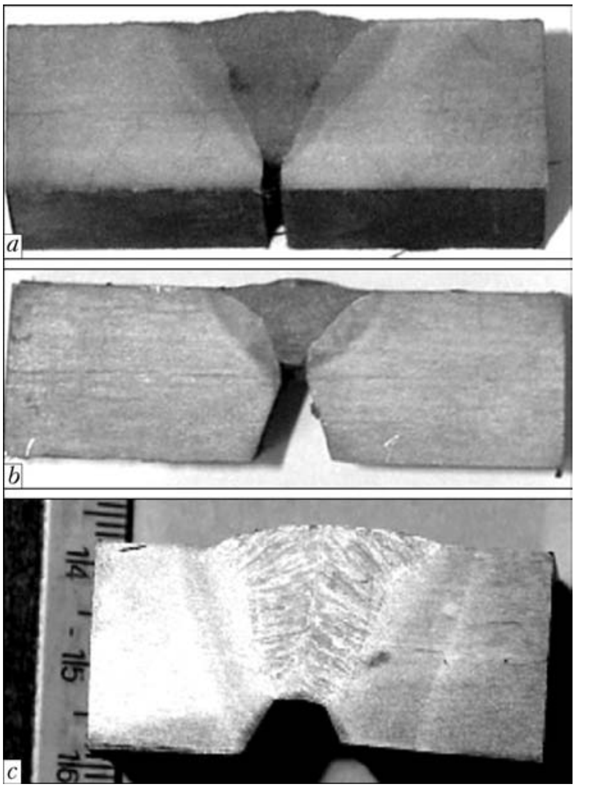


Figure 8. Typical macrosections manufactured of technological samples «rigid contour welding» of steel 06GBD: *a*, *b* — mechanized welding in shielding gases; respectively, V- and X-shaped preparation of edges 12 mm thick; *c* — automatic submerged arc welding; X-shaped preparation of edges 20 mm thick

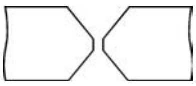
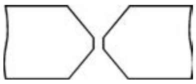
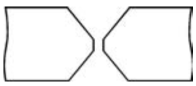
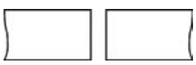
Basing on the carried out tests of effect of the thermal cycles of welding on the structure and properties of HAZ metal of welded joints of steel 06GBD, the rates of cooling in the temperature range of 600–500 °C were established, and modes of automatic submerged arc welding were calculated (Table 4).

The investigations, carried out at the E.O. Paton Electric Welding Institute and shop conditions, showed that in welding of steel 06GBD the producing of joints with mechanical properties equal to those of base metal is provided by the welding consumables produced by the industry: wire Sv-08G2S in combination with shield-

Table 4. Recommended modes of automatic welding of butt joints with edge preparation of steel 06GBD of strength class C390 under the flux using wire of solid section of 4 mm diameter, and relative energy inputs and cooling rates of weld and HAZ metal

δ, mm	Welding mode			$q_{h.i}$, J/cm	$w_{6/5}$, °C/s, at initial temperature of welded joint, °C			
	I_w, A	U_a, V	v_w, m/h (cm/s)		+5	+20	+120	+160
40	700–750	30–34	25 (0.7)	24,600–29,870	25.6–21.4	24.5–20.2	15.7–12.8	12.7–10.2
32	550–600	30–34	20 (0.555)	24,380–30,133	22.4–20.5	21.5–19.7	14.0–12.0	11.5–9.6
20	550–600	30–34	20–22 (0.555–0.611)	22,141–30,133	24.5–14.4	22.8–12.9	12.8–6.1	9.01–4.20
14	450–500	30–32	26 (0.722)	15,325–18,166	27.0–18.6	25.1–16.2	11.8–7.6	8.1–5.3
12	450–500	30–32	28 (0.777)	14,241–16,879	21.5–14.3	19.4–12.8	8.9–5.7	5.9–3.8

Table 5. Mechanical properties of welded joints of steel 06GBD of the strength class C390 produced using automatic arc welding under the flux AN-47 and wire Sv-10NMA of 4 mm diameter

δ, mm	Shape of edge preparation	σ_t, MPa	α_{bend}, deg	KCU, J/cm^2				KCV, J/cm^2				HV_{max}
				Weld center		HAZ		Weld center		HAZ		
				+20	−40	+20	−40	+20	−40	+20	−40	
40		528	180	183.5	93	330	330	142	64	305	300	208
32		534	180	160	101	334	315	146	56	300	298	208
20		550	180	196	102	347	344	122	40	No data	No data	208
14		566	180	194	95	326	314	157	43	306	300	208
12		582	180	166	110	290	289	142	55	298	296	201
12		560	180	214	91	330	322	123	41	305	295	192

ing gas mixture Ar + 18 % CO_2, and also wire Sv-10NMA in combination with the flux AN-47. The typical values of mechanical properties of welded joints of the steel 06GBD of different thickness are given in Table 5. It should be noted that welding consumables mentioned above provide required level of mechanical properties also on steel 06G2B of the strength class C440.

The recommended welding modes and welding consumables found application in manufacture of critical welded metal structures of tanks of steel 06G2B of the high capacity for oil and oil products, and also in manufacture of bridge metal structures of steel 06GBD. The experience of service of these structures of sparsely-alloyed steels 06G2B in Ukraine and Belarus under the normal climatic conditions proves the high reliability and correct application of welding technologies.

1. Mikhoduj, L.I., Kirian, V.I., Poznyakov, V.D. et al. (2003) Sparsely-alloyed high-strength steels for welded structures. *The Paton Welding J.*, **5**, 34–37.
2. Grabin, V.F., Golovko, V.V., Kostin, V.A. (2004) Morphological peculiarities of microstructure of weld metal from low-alloy steels with ultralow content of carbon. *Ibid.*, **7**, 15–20.
3. Goldshtejn, M.I., Gladshtejn, L.I., Golovanenko, S.A. (1977) Carbonitride strengthening of low-alloy steels. *Stal*, **9**, 833–837.
4. Poznyakov, V.D., Barvinko, A.Yu., Barvinko, Yu.P. et al. (2012) Cold resistance and lamellar fracture resistance of welded joints on steel 06GB-390. *The Paton Welding J.*, **3**, 35–39.
5. Ivashchenko, G.A., Demchenko, Yu.V. (1990) Principles of choice of chemical composition of higher strength and cold resistance steels for welded structures. In: *Advanced methods for producing of structural steel and cast iron welded joints*. Kiev: PWI, 110–116.
6. Pilyushenko, V.L. (1987) Influence of microalloying on service characteristics of steels. *Stal*, **10**, 24–26.
7. Grigorenko, G.M., Kostin, V.A., Orlovsky, V.Yu. (2008) Current capabilities of simulation of austenite transformations in low-alloyed steel welds. *The Paton Welding J.*, **3**, 22–24.
8. Sarzhevsky, V.A., Sazonov, V.Ya. (1981) Unit for simulation of welding thermal cycles on the base of MSR-75 machine. *Avtomatich. Svarka*, **5**, 69–70.

Received 07.02.2013