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USE OF STEELS OF THE STRENGTH CLASS C350–C490 IN THE PRODUCTION OF BUILDING WELDED STRUCTURES

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The effect of thermal cycles of arc welding on the structure and mechanical properties of metal of the heat-affected zone of welded joints of microalloyed structural steels of the strength class from C350 to C490 was investigated. It was established that as a result of the action of thermal cycles of welding, metal structure of the heat-affected zone of most microalloyed steels of the strength class from C350 to C490, except for steel 09G2SYuch, remains stable bainite in a wide range of cooling rates, and mechanical properties do not change significantly. As a result of welding, at moderate cooling rates the structure of the heat-affected zone metal in the steel 09G2SYuch can change from bainitic to bainito-martensitic and martensitic as the metal cooling rate increases. As a result of that, the values of static strength and impact toughness of the metal are increasing and its ductile properties are reduced. 12 Ref., 5 Tables, 7 Figures.

Keywords: structural steels, thermal cycle of welding, metal structure, mechanical properties, welded building structures

One of the main tasks in the modern development of industry is to increase the technical and economic performance of machines, mechanisms and engineering structures on the basis of reducing their specific metal consumption, increasing service reliability and life. In world practice, this is achieved through the use of high-strength steels with the yield strength of 350 MPa or higher during manufacture of welded metal structures.

In particular, low-alloy high-strength steels of the strength class C355–C490 are widely used in bridge construction, in the production of tanks for storage and processing of gas and oil, in the manufacture of building structures, etc. As far as the vast majority of the mentioned metal structures are welded, such steels have certain requirements, namely, they should be well welded, provide high ductility and equal strength of welded joints, as well as the values of impact toughness at the level of the requirements, which are regulated by the state building standards, which have undergone some changes in recent years. These changes, first of all, relate to the values of impact toughness and relative reduction in area of rolling surface in the Z-direction. According to the modern requirements, steels and, respectively, weld metal and metal of heat-affected zone (HAZ) of welded joints should have impact toughness $KCV^{-20} \geq 25$ J/cm^2 for steels with $\sigma_y = 290$–390 MPa and $KCV^{-40} \geq 25$ J/cm^2 for steels with $\sigma_y \geq 390$ MPa and relative reduction in area in the Z-direction (ψ_z) of not less than 35, 25 and 15 % for the first, second and third groups of structures, respectively.

Until now, during the manufacture of building structures in the CIS countries, low-alloy steels of the strength class C350–C390, such as 09G2S, 10KhSND, 15KhSND and other are still widely used, which were developed in the times of the USSR (Table 1). All the mentioned low-alloy structural steels, listed in Table 1 completely meet the modern requirements to the static strength and ductile properties of steels along and across the rolling surface (Table 2). In most of them the impact toughness is also at the level of these requirements. But in order to maintain the required level of *KCV* of HAZ metal, the cooling rate of welded

Table 1. Requirements to the chemical composition of increased and high-strength steels for building structures

Steel grade	Mass fraction of elements, wt.%										
	C	Si	Mn	Cr	Ni	Mo	V	Al	Cu	S	P
09G2S	≤0.12	0.5–0.8	1.3–1.7	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
15KhSND	0.12–0.18	0.4–0.7	0.4–0.7	0.6–0.9	0.3–0.6	–	–	–	0.2–0.4	<0.035	<0.03
17G1S	0.15–0.20	0.4–0.6	1.15–1.6	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
10G2S1	≤0.12	0.8–1.1	1.3–1.65	<0.3	<0.3	–	–	–	<0.3	<0.035	<0.03
10KhSND	≤0.12	0.8–1.1	0.5–0.8	0.6–0.9	0.5–0.8	–	–	–	0.4–0.6	<0.035	<0.03

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Table 2. Requirements to the mechanical properties of increased and high-strength steels for building structures (not less than)

Steel grade	σ_y, MPa	σ_t, MPa	δ_5, %	KCU^{-40}, J/cm^2
09G2S	350	500	21	34
15KhSND	350	500	21	29
17G1S	350	500	22	29
10G2S1	390	520	19	29
10KhSND	390	530–660	19	29

Table 3. Requirements to the mechanical properties of new microalloyed steels of increased and high-strength for building structures (not less than)

Steel grade	σ_y, MPa	σ_t, MPa	δ_5, %	KCV^{-40}, J/cm^2
06GB, 390	390	490	22	98
06G2B, 440	440	540	22	98
09G2SYuch	450	570	19	29
10G2FB	490	565	22	29

joints in the temperature range of 600–500 °C ($w_{6/5}$) should be in the range of 15–20 °C/s. This requires a significant limitation of welding modes, which complicates the technological process and makes its efficiency low. In addition, ψ_z in such steels does not exceed 15 %, which limits their use in welded elements operating in the direction of the thickness of a rolling surface.

Since the 1990s, some changes occurred in the metallurgical industry due to significant economic and technical transformations. The mass transition of enterprises to economic independence contributed to the creation of steels, the production of which is most economically advantageous for specific economic conditions of the combine plants. The intensive integration of domestic metallurgy into the world economy caused a necessity in the revision of the standards to steel quality evaluation. First of all, it concerns the evaluation of their impact toughness. In addition to the approach to determination of impact toughness, generally accepted in the domestic industry, based on the results of examination of specimens with a U-shaped notch, the specimens began to be used, that have a V-shaped notch. Their use during tests provides a more accurate evaluation of the ability of steels to resist fracture. At the same time, such an approach revealed certain defects in domestic steels. In this regard, a need arose to modernize the existing steels and create the new steels that would satisfy the ever-increasing requirements of production. As a result, in recent years domestic metallurgical plants mastered the production of new steels of increased and high strength that are manufactured by domestic and international standards and completely meet the Eurostandard requirements.

High strength, ductility and impact toughness (Table 3) are obtained by modern high-strength structural steels due to formation of fine-grained structure of a certain composition in the metal. This is achieved both due to alloying of steels (as a rule, they contain manganese, silicon limited to 0.5 %, carbon — to 0.15 %, nitrogen — to 0.012 % and microalloyed separately or in combination with vanadium, aluminum, niobium, cerium), as well as due to controlled rolling or special heat treatment of rolled steel (Table 4).

Taking into account that the mentioned high-strength structural steels, which are manufactured at Ukrainian metallurgical enterprises, have exceptionally high mechanical properties, all of them were recommended and included in the State Building Regulations as those that can be used in the manufacture of building metal structures. To ground such possibility, at PWI the comprehensive investigations were carried out, which showed a good weldability of these steels and allowed determining the conditions of welding at which joining of the mentioned steels would fully meet the modern requirements to metal structures.

Evaluation of steels weldability consists in determining the optimal welding conditions, at which the probability of cold cracks formation in the joints and in the metal of the heat-affected zone of the structures is eliminated, that will facilitating the reduction in the strength, ductility and cold resistance of the metal.

In contrast to rolled steel, the formation of structure in the HAZ metal of welded joints of high-strength steels is significantly affected by the thermal

Table 4. Requirements to the chemical composition of new microalloyed steels of increased and high strength for building structures

Steel grade	Mass fraction of elements, wt.%										
	C	Si	Mn	Mo	Al	Nb	V	Ce	Cu	S	P
06GB, 390	0.04–0.08	0.25–0.50	1.1–1.4	≤0.08	≤0.05	0.01–0.03	0.02–0.05	–	<0.3	<0.01	<0.025
06G2B, 440	0.04–0.08	0.25–0.50	1.3–1.6	≤0.10	0.02–0.05	0.03–0.05	0.03–0.07	–	<0.3	<0.01	<0.025
09G2SYuch	0.08–0.11	0.3–0.6	1.9–2.2	–	0.035–0.065	–	–	0.002–0.005	0.3–0.6	<0.015	<0.02
10G2FB	≤0.15	≤0.35	≤1.7	≤0.3	0.02–0.03	≤0.08	≤0.1	–	–	<0.01	<0.02

cycle of welding (TCW) [1–9]. The most significant changes in the structure of steel during welding occur in the region of overheating of the HAZ metal, i.e. in that area, which is located in the immediate vicinity to the weld and is heated to the temperature of 1300–1150 °C. During arc welding, TCW parameters depend on many factors. The most important among them are heat input of welding, initial temperature of the metal and its thickness and type of welded joint. With increase in the heat input of welding and initial temperature of the metal, the rate of cooling the HAZ metal in the temperature range of 600–500 °C ($w_{6/5}$, °C/s) decreases, and with increase in the metal thickness — it grows. Based on these considerations, we selected namely the index $w_{6/5}$ as a criterion that will allow comparing the reaction of steels to TCW and determining how the conditions of heating and cooling of the metal affect its structure and mechanical properties.

The investigations, the results of which are given in this article, were performed with respect to the thermal cycle of welding specimens and the specimens produced from the deposits on the plate. The effect of thermal cycles of welding on the HAZ metal structure was studied by dilatometry examinations and optical microscopy [10]. The mechanical tests on static tension and impact bending were performed using the standard specimens: type II according to GOST 6996–66 and type IX according to GOST 9454–78.

To determine the effect of chemical composition and cooling conditions of the metal on its structure, the austenite transformation diagrams were used, which were plotted taking into account the processes that occur during welding. At the same time, in order to provide a high austenite resistance typical for welding, such heating conditions (w_h) were selected when plotting the transformation diagrams, under which the individual features of steels with respect to the susceptibility of grain growth became to be quite clearly revealed. Usually, during dilatometric investigations, the specimens heating rate is set within 150–300 °C/s [11]. In our investigations, it was 150 °C/s. The cooling rates of dilatometric specimens were selected on the basis of the need to provide such cooling conditions in the temperature range of the least austenite stability that will be as close as possible to the conditions of cooling the metal at the overheating region of the heat-affected zone of the joints produced on the conditions characteristic for arc welding processes.

The heating rate was controlled by changing the current according to the set program, which passed through the specimen and the cooling rate was controlled by cooling the devices that transmit the current from the heating machine to the specimen by water, blowing the specimen with inert gas.

Due to the rigid fixing of specimens in the heating machine, the processes of development of inner deformations are simulated on them in the region of uniform heating, which according to the value and nature of changes are close to the longitudinal inner deformations formed at the region of HAZ metal overheating in arc surfacing of metal layer on the edges of plates.

The dependencies plotted on the basis of the austenite transformation diagram related to changes of structural components occurring at different cooling rates at the region of HAZ metal overheating of new high-strength microalloyed steel structures, are presented in Figure 1.

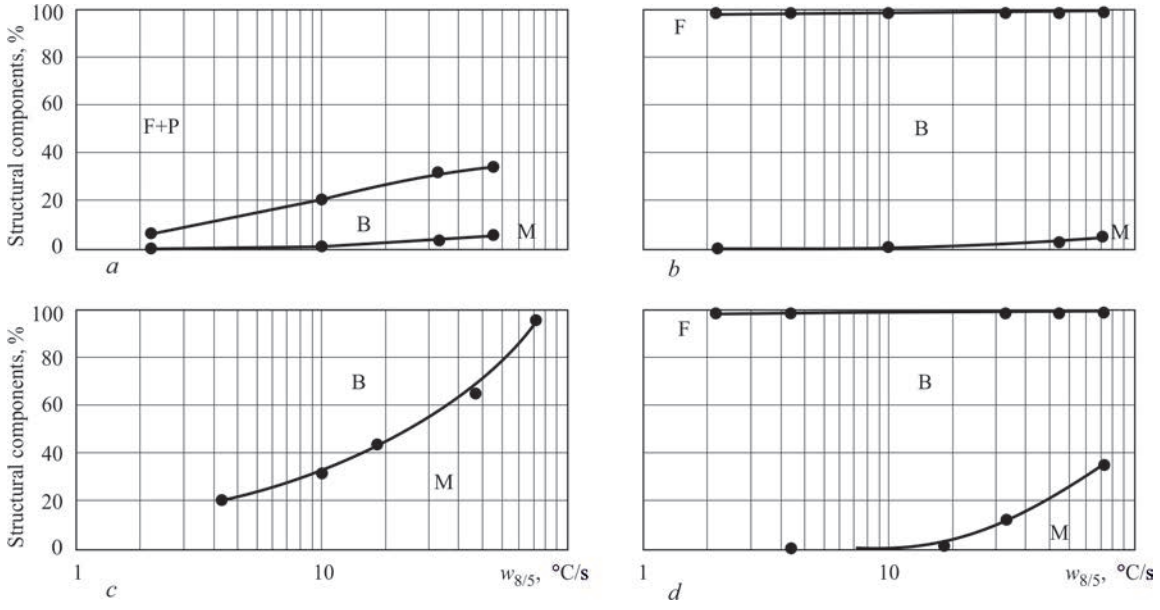

Figure 1. Diagrams of structural transformations of austenite at the overheating region of HAZ metal of low-alloy high-strength steels of type 06GBD (*a*); 06G2B (*b*); 09G2SYuch (*c*); 10G2FB (*d*)

Unlike low-alloy steels 09G2S, 10KhSND and 15KhSND, in which the transformation of austenite largely depends on the cooling rate of the metal and can occur in ferrite (at a moderate, up to 10 °C/s, cooling rate) and in bainite and martensite regions at higher cooling rates, in microalloyed steels of grades 06GBD, 06G2B and 10G2FB, it occurs in a significantly different way. In almost all the investigated range of cooling rates, the austenite transformation at the overheating region of HAZ metal of steels 06G2B and 10G2FB occurs mainly with the formation of bainite, and in steel 06GBD — with the formation of ferrite, pearlite and bainite [1, 2].

An exception among the investigated microalloyed structural steels is the steel of grade 09G2SYuch [5]. In it, as in most low-alloy high-strength structural steels, the transformation of austenite occurs with the formation of bainite and martensite.

Further let us consider how the conditions of cooling metal under the influence of TCW affect its mechanical properties.

To obtain the information on the effect of TCW on the values of static strength and plastic properties of HAZ metal of welded joints, standard tensile specimens are used made from the investigated metal bricks preliminary treated according to the thermal cycle of welding. This is associated with the fact that the sizes of HAZ and its separate components are usually much smaller than the sizes of specimens being tested. Therefore, in this case, the investigations related to changes in the yield strength, tensile strength, elongation and reduction in area occurring in the HAZ metal of steels under the influence of TCW were obtained using the abovementioned approach. During the investigations, 13×13×150 mm bricks were used which were treated according to the thermal cycle of welding in the MCR-75 installation, designed at PWI [12].

For modelling TCW, the specimens were heated by a passing current to the temperature of 1250 °C (heating rate is 150 °C/s), and then cooled according to a set program. By regulating the intensity of blowing specimens with inert gas, their cooling rate in the temperature range of 600–500 °C was varied from 3 to 50 °C/s. The mode of heating-cooling specimens was controlled by 0.5 mm diameter chromelalumel thermocouple, and the cooling rate was evaluated according to the results of processing oscillograms, which were recorded in the oscilloscope 117/1 in temperature-time coordinates.

For testing on static (short-term) tension, from the bricks treated over TCW, the specimens of type II were mechanically manufactured according to GOST 6996–96 (2 specimens for each cooling rate). The tests were performed in accordance with GOST 6996–66 at a temperature of 20 °C. The results of the investigations are shown in Figure 2.

They indicate the fact that when the metal on the HAZ overheating region is cooled at a cooling rate $w_{6/5}$, which does not exceed 10 °C/s, it can be softened. This is manifested in the fact that the values of its yield strength are decreased by 10–25 % in re-

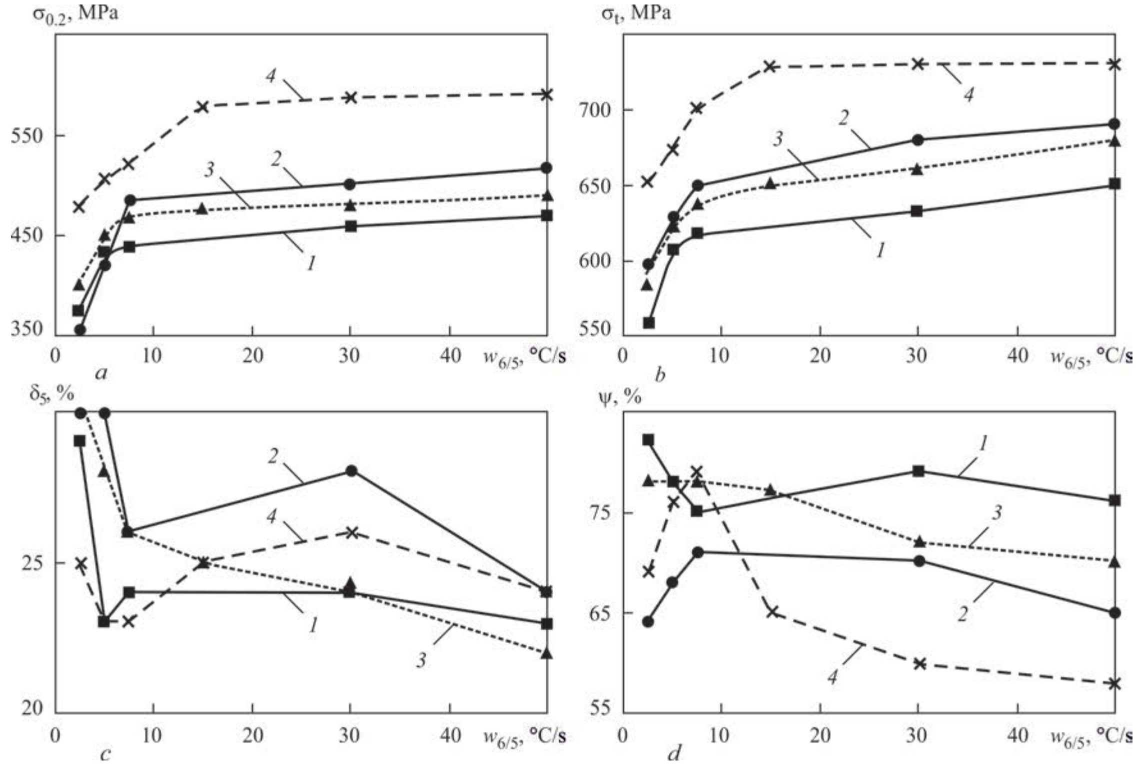

Figure 2. Effect of cooling rate $w_{6/5}$ on the values of yield strength (*a*), tensile strength (*b*), elongation (*c*) and reduction in area *(d)* of HAZ metal of steels: 06GBD (*1*); 09G2SYuch (*2*); 06G2B (*3*); 10G2FB (*4*)

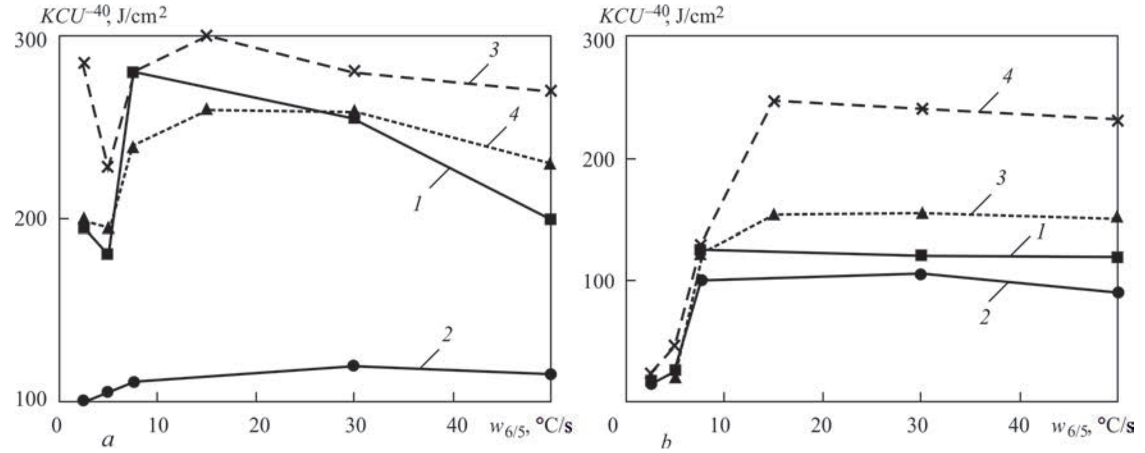

Figure 3. Effect of cooling rate $w_{6/5}$ on the values of impact toughness of HAZ metal of steels 06GBD (*1*); 09G2SYuch (*2*); 06G2B (*3*); 10G2FB (*4*)

lation to the base metal. In the range of rates from 3–10 °C/s, the values of $\sigma_{0.2}$ and σ_t of the HAZ metal are rapidly increased and subsequently they grow rather slowly. This is quite natural, since as the data in Figure 2 show, the HAZ metal structure of high-strength microalloyed structural steels is stable over a wide range of cooling rates. The ductile properties of HAZ metal in these steels are also somewhat decreased, but remain quite high and stable over a wide range of cooling rates.

The effect of thermal cycles of welding (TCW) on the values of impact toughness of the HAZ metal of the investigated structural steels was studied using a «bead test» according to GOST 13585–68.

To provide the conditions of cooling welded joints with the metal of different thickness characteristic for processes of manual, mechanized in shielding gases and automatic submerged-arc welding, namely in the range from 3.0 to 50 °C/s, the plates with a thickness of 20 mm were produced using the wire of solid cross-section with a diameter of 4.0 mm under the layer of flux in the modes, shown in Table 5.

To determine the impact toughness, from the «bead sample» the billets were cut, which were made of specimens with a cross-section of 10×10×55 mm (type VI with a round notch and type IX with a sharp notch). The tests of specimens were carried out at the temperature of –40 °C.

The investigations, the results of which are given in Figure 3, showed that under the conditions of cooling HAZ of welded joints at a rate $w_{6/5}$ which is higher than 5 °C/s, the impact toughness of the metal KCV^{-40} on the overheating region is provided at a level significantly exceeding the current requirements to building metal structures. At a slower cooling, the values KCV^{-40} can be reduced to critical levels.

In general, the carried out investigations showed that the new microalloyed structural steels of the strength classes C350–C490 as to their mechanical properties are superior to low-alloy structural steels of the strength classes C350–C390, which were developed in the USSR, are more technological and allow providing a complex of properties of welded joints at the level of modern world requirements to metal building structures. Namely this was the impetus to the fact that since the beginning of this millennium, such steels began to be gradually introduced into production in Ukraine for the manufacture of welded metal structures for the needs of building industry in bridge construction, mechanical engineering, etc.

In particular, the technological processes of arc welding developed in 2003 on the basis of the above-mentioned results of investigations, were introduced in the manufacture of unique building structures during construction of the tank in Brody for the stor-

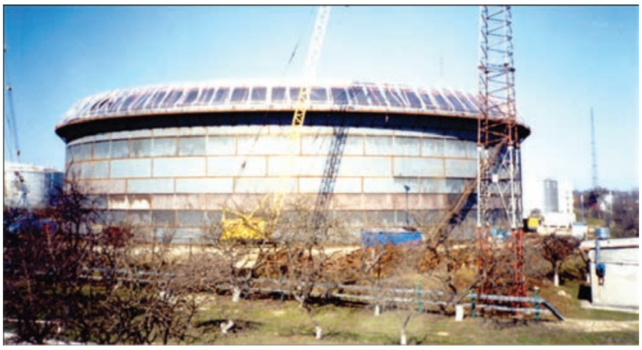

Figure 4. Tank for oil storage with a capacity of 75000 m^3 of rolled steel 06G2B-440

Table 5. Modes on which surfacing on the plates was performed

I_w, A	U_a, V	v_w, m/g	Q_w, kJ/cm	$w_{8/5}$, °C/s
580–600	34–38	9.8	62.7	3
580–600	34–38	14.7	41.8	6
580–600	34–38	17.3	35.7	10
580–600	34–38	21.7	28.6	20
380–400	30–32	15.2	23.0	30
380–400	30–32	20.1	16.7	50

Figure 5. Construction of the Podilskyi Bridge crossing in Kyiv, the arches of which are made of steel 06GBD of the strength class C390

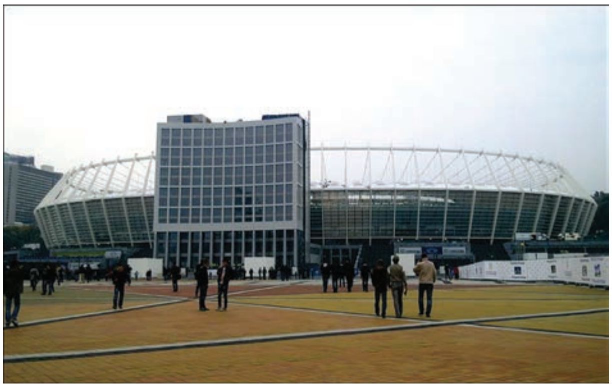

Figure 6. Olimpiyskyi NSC in Kyiv

age of oil with a capacity of 75000 m^3 of rolled steel 06G2B of the strength class C440 (Figure 4).

In the future, the experience gained during this work was used in the manufacture of steel structures of tanks with a capacity of 50000 m^3 during modernization of the tank farm in Mozyr (Republic of Belarus) on the region of main oil pipelines. The metal structures were made of rolled steel 06GB of the strength class C390 with a thickness of 20–30 mm with the use of mechanized welding in mixture of gases (82 % Ag + 18 % CO_2) with a solid cross-section wire.

In 2006, steel 06GBD of the strength class C390 and technology of its welding were used in the manufacture of metal structures for the Podilskyi bridge crossing over the Dnipro River in Kyiv at the I.V. Babushkin Dnipropetrovsk Metal Structure Plant (Figure 5).

Figure 7. Repair of blast furnace DP-2 at the OJSC «Azovstal Steel Plant» using rolled steel 06G2B of the strength class C440

During preparation for the European Football Championship EURO-2012 in Ukraine, the technologies of automatic submerged-arc welding, mechanized welding, welding in shielding gases and manual arc welding of steel S 355 J2 (analogue of steel 10G2FB of the strength class C355)) with the thickness of 16–100 mm were developed and certified. In 2010–2011, they were introduced during the manufacture and assembly of box-like metal structures for the fence roof over the Olimpiyskyi NSC (Kyiv) during its reconstruction. Welded metal structure with a total weight of 40 thous tons consists of 80 lower and facade columns with the length from 23 to 25.5 m, weight from 25 to 30 tons each, as well as beams of the lower and upper compressed rings (Figure 6).

The experience gained during the reconstruction of the Olimpiyskyi NSC contributed to the successful fulfilment of a new task in 2013, namely, in the development of welding technology for manufacture and assembly of metal structures of tubular cross-section of steel 10G2FBYu of the strength class C490 for the football stadium with 45000 spectators.

New structural high-strength steels become increasingly used in Ukraine in the construction and major repair of engineering structures of metallurgical enterprises. In particular, steel of grade 06G2B of the strength class C440 and welding technologies developed at the PWI were introduced during the repair of the blast furnace DP-2 at the OJSC «Azovstal Steel Plant» (Figure 7), as well as at the Yenakiieve and Kryvorizhsky metallurgical plants.

Conclusions

1. Unlike most structural low-alloy steels, the transformation of austenite into vanadium- and niobium-alloyed steels of the strength class from C350 to C490 at a continuous cooling over the thermal cycle of welding occurs mainly in the bainite region.

2. As a result of structural transformations occurring in steels under the effect of thermal cycles of welding, the values of static strength of the metal of the heat-affected zone of the welded joints increase and the ductile properties decrease.

3. A significant decrease in the values of impact toughness in the metal of the heat-affected zone of

welded joints of microalloyed structural steels is observed at $w_{6/5} \le 5$ °C/s. As the cooling rate increases, the impact toughness of the metal of the heat-affected zone grows rapidly, and in some steels it almost reaches the level of the base metal.

1. Zhdanov, S.L., Poznyakov, V.D., Maksimenko, A.A. Dovzhenko, V.A. et al. (2010) Structure and properties of arc-welded joints on steel 10G2FB. *The Paton Welding J.*, **11**, 8–12.
2. Poznyakov, V.D., Zhdanov, S.L., Maksimenko, A.A. et al. (2013) Weldability of sparcely-alloyed steels 06GBD and 06G2B. *Ibid*., **4**, 8–14.
3. Poznyakov, V.D., Zhdanov, S.L., Maksimenko, A.A. (2012) Structure and properties of welded joints of steel S390 (S355 J2). *Ibid*., **8**, 6–10.
4. Poznyakov, V.D., Zhdanov, S.L., Zavdoveev, A.V. et al. (2016) Weldability of high-strength microalloyed steel S460M. *Ibid*., **12**, 23–30.
5. Mikhoduj, L.I., Kirian, V.I., Poznyakov, V.D. et al. (2003) Sparsely-alloyed high-strength steels for welded structures. *Ibid*., **5**, 34–37.
6. Ufuah, E. (2013) Elevated temperature mechanical properties of butt-welded connections made with high-strength steel grades S355 and S460M. In: *Proc. of Int. Conf on Design, Fabrication and Economy of Metal Structures (Miskolc, Hungary, April 24–26)*, 407–412.
7. Nazarov, A., Yakushev, E., Shabalov, I. et al. (2014) Comparison of weldability of high-strength pipe steels microalloyed with niobium and vanadium. *Metallurgist*, 7(**9–10**), 911–917.
8. Ragu Nathan, S., Balasubramanian, V., Malarvizhi, S., Rao, A.G. (2015) Effect of welding processes on mechanical and microstructural characteristics of high strength low alloy naval grade steel joints. *Defense Technology*, **11**, 308–317.
9. Show, B.K., Veerababu, R., Balamuralikrishnan, R., Malakondaiah, G. (2010) Effect of vanadium and titanium modification on the microstructure and mechanical properties of microalloyed HSLA steel. *Mater. Sci. Eng. A*, **527**, 1595–1604.
10. Grigorenko, G.M., Kostin, V.A., Orlovsky, V.Yu. (2008) Modern possibilities for modeling of austenite transformations in low-alloyed steel welds. *The Paton Welding J.*, **3**, 31–34.
11. Seyffarth, P. (1982) *Schweiss – Z.T.U.* Schaubilder Berlin, VEB Verlag.
12. Sarzhevsky, V.A., Sazonov, V.Ya. (1981) Installation for simulation of welding thermal cycles based on machine MCR75. *Avtomatich. Svarka*, **5**, 69–70 [in Russian].

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