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TECHNOLOGY OF MIG WELDING OF CHROMIUM STEEL OF MARTENSITIC GRADE CA-6NM

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ABSTRACT

The weldability of the martensitic steel CA-6NM was investigated and the fundamental technology of its mechanized welding in a mixture of shielding gases was developed according to the requirements for the manufacture of critical parts and assemblies of the hydroturbine equipment, as well as rewelding of casting defects. According to the strength level of the steel, the welding wire Thermanit 13/04 Si of a solid cross-section with a diameter of 1.2 mm and one of the variants of the shielding mixture Mix 1 (82 % Ar + 18 % CO_2) were selected and comprehensively investigated according to EN 12072/G 134 (Germany). It was established that in order to prevent the formation of cold cracks in welded joints, it is necessary to perform welding of this steel with preheating and concurrent heating up to 150–200 °C and a mandatory postweld tempering at the temperature of 600 °C. The developed technology provides a significant improvement in mechanical properties of welded joints and weld metal (by 30–35 % higher than that specified by the requirements to the level of values for base metal of chromium steel CA-6NM). Certification of the technology was carried out and recommendations for its use in production at JSC "Ukrainian Energy Machines" were worked out.

KEYWORDS: mechanized welding, martensitic steel class, mixture of shielding gases, diffusible hydrogen, cold cracks, mechanical properties, structure

INTRODUCTION

In Ukraine critical parts and welded components of hydroturbine equipment, exposed to intensive cavitation, corrosion and abrasive wear in service are manufactured using chromium steels, both of local grades 06Kh13N4MD, 06Kh12N3D, and foreign grades, in particular CA-6NM steel (03Kh13N5M) [1]. A feature of manufacturing such components of hydraulic radial-axial turbines is a great diversity of individual types of parts and welded structures, which are to be joined and which include, for instance joining stamped or cast blades, rolled and cast rims to make the impeller, as well as rewelding possible casting defects in parts of a large weight of up to 50 t. At the same time, manufacturing cast-welded structures requires a technology of joining to other steel grades of the same class (06Kh12N3DL, 06Kh12N4ML) under the conditions of large thicknesses and considerable rigidity of the parts. Here, it is necessary to preserve high mechanical properties of welded joints of these steel grades, and to focus on the requirements of CA-6NM steel. At present, at manufacture of welded parts and components of hydroturbine equipment from chromium steels of martensitic class, in particular, for rewelding casting defects, "Ukrainian Energy Machines" JSC, mainly, uses coated-electrode manual electric arc and mechanized CO_2 welding, which have a number of drawbacks [2–4]. Taking into account the welding-technological properties, mechanized welding, for instance in a mixture with shielding gases ($Ar + CO_2$), has significant advantages, compared to the above processes [5, 6]. In welding in a gas mixture of 82 % Ar + 18 % CO_2 the region of welding modes with short-circuiting of the arc gap is absent (just the region of drop transfer and jet transfer is observed). Here, electrode metal losses for burning-out and spatter are reduced, weld formation quality is improved, resistance to pore formation and technological strength are increased, labour consumption in the joint cleaning from spatter is reduced, and there is a real possibility for improving the values of welded joint mechanical properties.

Therefore, development and introduction of mechanized welding in a shielding gas mixture in manufacture of components of hydroturbine equipment from chromium martensitic steel and rewelding casting defects is an urgent task. In this connection, the objective of this work was investigation and development of scientifically substantiated principles of the technology of mechanized welding of CA-6NM steel in a mixture of shielding gases, which allow improvement of the technological strength, in particular cold cracking resistance of welded joints and ensuring their high service properties.

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

Steel grade	C	Si	Mn	Cr	Ni	Mo	S	P	Other elements
							Not more than		
06Kh12N3D steel to TU 1081425-86	≤ 0.06	≤ 0.3	≤ 0.06	12.0–13.5	2.8–3.2	–	0.025	0.025	Cu–0.50–1.10 W+V
CA-6NM steel in as-delivered condition (PWI data)	0.037	0.20	0.43	11.81	3.9	0.47	0.016	0.017	–

EXPERIMENTAL MATERIALS AND PROCEDURES

Chemical composition of chromium steels of steels of grades 06Kh12N3D and CA-6NM, considered in this work, is given in Table 1.

Selection of welding wire was based on its matching the chemical composition of the base metal, i.e. the possibility of its application for martensitic class steels with 13 % chromium. Alongside having a matching composition, the welding wire in mechanized welding should satisfy the requirements of equivalent strength by the mechanical properties — ensuring equivalent strength by all the indices with the material being welded.

Proceeding from analysis of the market of supply of welding consumables, 1.2 mm solid wire of Thermanit 13/04 Si grade of Thyssen (Germany) was selected. Chemical composition of the wire is given in Table 2. Previous evaluation of its welding-technological properties in mechanized welding in gas mixture Mix 1 showed the high stability in welding in all the positions in space with excellent weld formation, slight spatter and absence of any type of defects. Results of studying the chemical composition in the 7th layer of the deposited metal are given in Table 2. As we can see, it is characterized by a low content of such impurities as sulphur and phosphorus, and it is close to CA-6NM steel composition.

Requirements of GTI-407–2018 Instructions [1] to the mechanical properties of base metal and weld metal are given in Table 3.

The following investigation procedures were used during performance of this work:

- alcohol procedure of investigation of “pencil test” sample, produced by pouring the weld pool into a detachable copper mould [7] to determine the diffusible hydrogen concentration in the deposited metal (applied in shipbuilding);
- procedure of restored melting of the sample in the flow of high-purity carrier-gas to determine the concentration of residual gases in the cast sample metal;
- procedure for determination of the equivalent of impurities in the weld meal [8], for evaluation of simultaneous influence of the concentration of oxygen, sulphur and phosphorus $[P_E] = O] + 0.8 [S] + 0.7 [P]$, where [O], [S], [P] are the concentrations of oxygen, sulphur and phosphorus;

Table 2. Chemical composition of the wire and deposited metal, wt.%

Object of study	C	Si	Mn	Cr	Ni	Mo	S	P	Other elements
Thermanit 13/04 Si wire EN 12072/G 13/4	0.03	0.8	0.7	13.0	4.7	0.5	–	–	–
Metal deposited by Thermanit 13/04S wire (PWI data)	0.03	0.36	0.36	12.0	3.8	0.27	0.010	0.005	–

Table 3. Requirements to mechanical properties of the base and deposited metal

Object of study	Ultimate strength σ_t, MPa	Yield point σ_y, MPa	Relative elongation δ, %	Reduction in area ψ, %	Impact toughness J/cm^2 at 20 °C		Hardness, *HB*
					KCU	*KCV*	
06Kh12N3D steel (for comparison)	690	540	14.0	30.0	59	49	187–275
CA-6NM steel	755	550	15.0	35.0	≥ 50	–	–
Deposited metal (Thermanit 13/04 Si wire to EN 15971*)	800	≥ 680	≥ 15	–	–	≥ 50	250

*After high-temperature tempering for 600 °C for 8 h.

- procedure of quantitative evaluation of cold cracking susceptibility of the welded joints (Implant method), which envisages evaluation of the strength properties at delayed fracture of samples-inserts [9];
- procedure of qualitative evaluation of cold cracking susceptibility of welded joints [10];
- metallographic investigations of welded joint microstructure were conducted using optical light microscope Neophot-32 with connected to it optical module based on a digital photocamera of Olympus C-5060 type for photorecording of images of the microstructures and nonmetallic inclusions;
- procedure of etching welded joint macrosections in 30 % water solution of iron chloride ($FeCl_3$);
- electrolytic etching of microsections in 10 % aqueous solution (distilled water) of chromic acid. Etching mode was as follows: 12–15 V voltage, 10–15 s etching time. Microstructure is revealed with repolishing of the section surface on cloth with chromium oxide powder deposition on it;
- determination of welded joint metal hardness in TP-5 instrument.

INVESTIGATION RESULTS AND THEIR DISCUSSION

Ensuring minimal gas saturation of the weld metal is one of the most important welding-technological properties of welding consumables. Diffusion-mobile oxygen has a particularly noticeable influence on the technological strength of the metal of the weld and HAZ. Concentration H_d of diffusion-mobile hydrogen was determined in the weld metal deposited with the studied wire. It was established that average value of H_d is on a very low level (<0.1 cm^3/100 g of the deposited metal). Special attention was also given to oxygen content in the deposited metal, as in the base metal it determines the volume fraction of nonmetallic inclusions, and in the deposited metal it is one of the key factors of weld metal impact toughness. Results of investigation of weld metal saturation by such gases as oxygen, nitrogen and residual hydrogen are given in Table 4. They show that gas content in the deposited metal is practically the same at different welding processes and it satisfies the specified requirements.

Impurities (sulphur, phosphorus and oxygen) are known to have a negative influence on the ductile properties and impact toughness of the weld metal. The notion of impurity equivalent [P_E] was introduced by the procedure in work [8]. Introduction of the notion of impurity equivalent allows reducing the multiple correlation to two variables and comparing the embrittlement of the weld metal in the form of oxide inclusions, sulphur and phosphorus, despite the existing differences in the behaviour of these impurities. It was found that a significant ductility drop is observed at [P_E] ≥ 0.08 % with a simultaneous increase in ultimate tensile strength [8]. At calculation of oxygen and sulphur and phosphorus content in the metal deposited with Thermanit 13/04 Si wire in shielding gas mixture Mix 1, [P_E] is equal to 0.07%. This is indicative of significant loss of sulphur and phosphorus as a result of such an active impact of oxygen, which allows obtaining an admissible value of P_E at application of mechanized welding by the mentioned welding wire. Thus, chemical composition of weld metal, its concentration of diffusible hydrogen and content of gases (O_2, N_2 and H) fully meet the specified requirements and should promote high crack resistance and the required level of mechanical properties of welded joints of CA-6NM steel (Table 3).

Weldability of martensitic class steels with chromium fraction of 13% is characterized by a higher cold cracking susceptibility of the joints. The determinant role in this phenomenon is attributed to martensitic transformation, and increased content of hydrogen and carbon [13]. As a result of thermal cycle of welding, steels of martensitic class undergo hardening, HAZ metal becomes harder, stronger and more brittle [14]. To eliminate the possibility of cold cracking, the authors of works [15–16] recommend minimizing the content of carbon and nitrogen in the base and filler material, here the weld should have not more than 10 % δ-ferrite. This is promoted by nickel content increased to 4–5 %. Maximal content of carbon and nitrogen in the base metal and welding consumables can be limited to the level of 0.02–0.03 %, and that of manganese and silicon usually is not more than 0.6–0.7 %. Optimal content of nickel of not more

Table 4. Content of residual gases in the deposited metal

Deposited metal	[O], wt.%	[N], wt.%	[H], ml/100 g Me
In a mixture of 82 % Ar +18 % CO_2 in welding with Thermanit 13/04 Si wire	0.059	0.043	2.46
In welding in 100 % CO_2 [11]	0.063–0.078	0.021	1.1
Manual welding by 4 mm TsL-20M electrodes [11]	0.0307	0.012	1.4
Automatic submerged-arc welding with AN-43M flux [12]	0.054	0.0138	1.6

than 5 % [17] also increases the content of highly ductile components in the welded joint structure.

For hardenable steels it is rational to evaluate the cooling cycle in the range from 500 to 300 °C, which reflects the thermokinetic features of austenite transformation in the martensite-bainite region. Also highly important for technological strength are the conditions of HAZ metal cooling after completion of phase transformation from ~200 to 100 °C. Delayed cooling at these temperatures ensures development of diffusion processes, with which the low-temperature tempering of martensite and atomic hydrogen escaping from the zone of possible cracking are associated.

Determination of actual cooling rates of the HAZ metal in the specified ranges was of interest when studying the delayed fracture susceptibility of CA-6NM steel. To assess the cold cracking susceptibility of CA-6NM steel and to determine the required preheating temperature at mechanized welding with 1.2 mm wire of Thermanit 13/04 Si grade in gas mixture Mix 1 a number of Implant tests were conducted at different preheating temperatures (100, 150, 200 and 250 °C) and without preheating, as well as at different level of loading of the samples-inserts. Welding was performed by a single stringer weld (bead) in the following mode: I_w = 180–200 A, U_a = 24–26 V, gas flow rate of 1000 l/h.

The cooling rate of the insert HAZ metal was determined by the thermal cycle (TC), welding characteristics were recorded to $T = 100$ °C. Cooling rate in the ranges of T = 600–500; 500–300 and 200–100 °C, which are denoted $w_{6/5}$, $w_{5/3}$ and $w_{2/1}$, was determined by calculation-graphic method by TC curve. Two to three curves from different TC, derived at one and the same heating temperature were processed in a similar way, and the obtained values were used to determine the average value of the cooling rate.

Results of evaluation of the delayed cracking susceptibility of welded joints of CA-6 NM steel are given in Figure 1. One can determine from the graph that absence of cold cracking susceptibility in mechanized welding by wire of Thermanit 13/04 Si grade in gas mixture Mix 1 is provided by preheating the base metal up to the temperature of 150 °C. It is found that the level of critical stress above the yield limit is ensured at preheating to 150–200 °C. Thus, welding should be performed after preheating at the level of 150–200 °C.

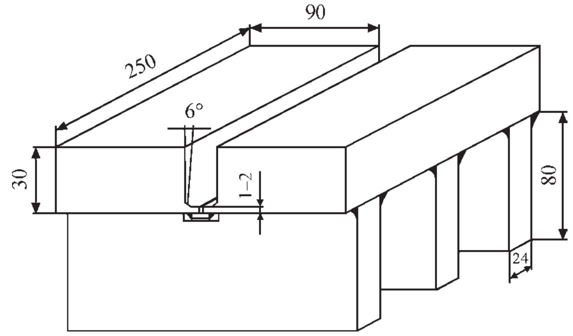

Figure 2. Rigid sample for making butt welded joint of CA-6NM steel

Qualitative evaluation of cold cracking susceptibility of the welded joints was performed by welding the first root pass in a rigid butt joint (Figure 2) at preheating temperatures, the optimal value of which was determined by the Implant method. Such a temperature was taken to be the value of 150 °C.

After cooling to room temperatures and soaking for 48 h the welded rigid samples were cut into transverse templates. The surfaces of welded joints were studied for crack initiation. Preheating of welded joints above 150 °C allows preventing cracklike defects.

EXPERIMENTAL-INDUSTRIAL VERIFICATION OF INVESTIGATION RESULTS

Butt samples of 200×300×30 and 200×300×40 mm size were prepared and welded, in order to study the structure and mechanical properties of weld metal in welded joints of CA-6NM steel made by mechanized welding in a shielding gas mixture. Figure 3 shows the shape of edge preparation for gas-shielded semi-automatic welding with dimensions, corresponding to type TP-6 according to DSTU EN 9692-1:2014.

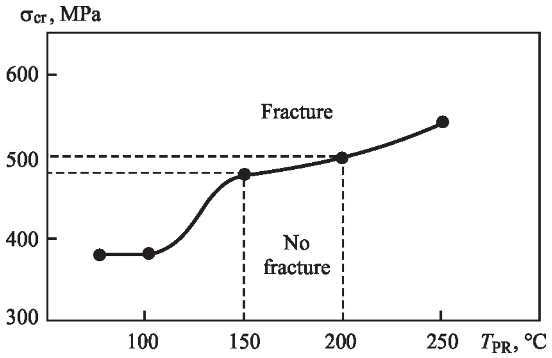

Figure 1. Curve of critical breaking stress for CA-6NM steel, depending on preheating temperature

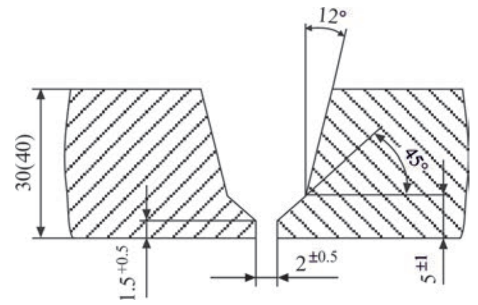

Figure 3. Shape of edge preparation of a joint of CA-6NM steel for mechanized welding

Table 5. Results of mechanical testing

Object of study	σ_t, MPa	σ_y, MPa	δ, %	ψ, %	Impact toughness, J/cm^2 at 20 °C		Bend angle, deg	Hardness, *HB*
					KCU	*KCV***		
Weld*	870.2–884.1	710.5–725.2	15.5–15.9	56.8–60.1	86.7–89.6–98.8	68.7–78.5–80.7	–	235–250
Welded joint*	814.3–827.7	–	–	–	–	–	130	–

*After high-temperature tempering at 600 °C, for 4 hours.
**At –40 °C *KCV* is equal to 53.9–59.7–59.9.

Welding the test butt joint was performed with preheating and concurrent heating up to the temperature of 150 °C. Mode of welding the root pass was as follows: I_w = 120–140 A, U_a = 19–22 V, shielding gas flow rate was 600 l/h. To fill up the groove the mode parameters were increased: I_w = 180–200 A, U_a = 24–26 V, gas flow rate was up to 1000 l/h. Welding was followed by heat treatment of the butt joint in the form of tempering at the temperature of 600 °C for four hours, with further cutting up of the samples into templates, from which samples were prepared for mechanical testing. When studying the mechanical properties of the weld metal, static tensile tests were conducted on samples, cut out of the weld metal along the weld. When studying the welded joints, the samples were cut out across the weld with the sample middle located on the fusion line. For static bending at normal temperature, the bending angle of welded joint samples should be not lower than that of the base metal. Weld metal testing for impact bending of samples with a round notch (*KCU*) was conducted at room temperature. Impact bend testing of samples with a sharp notch (*KCV*) was performed in the temperature range from +10 to –40 °C. Results of mechanical testing of the metal of the weld and welded joint of CA-6NM steel are given in Table 5.

Thus, mechanical characteristics of the metal of the weld and welded joint of CA-6NM steel, made by mechanized welding in a shielding gas mixture Mix 1, using Thermanit 13/04 Si wire, fully meet the requirements to welded joints of CA-6NM steel (see Table 3).

Figure 4. Macrosection of CA-6NM steel welded joint

Metallographic investigations were performed in order to evaluate the quality of base metal, welded joints and weld metal, as well as structural changes,

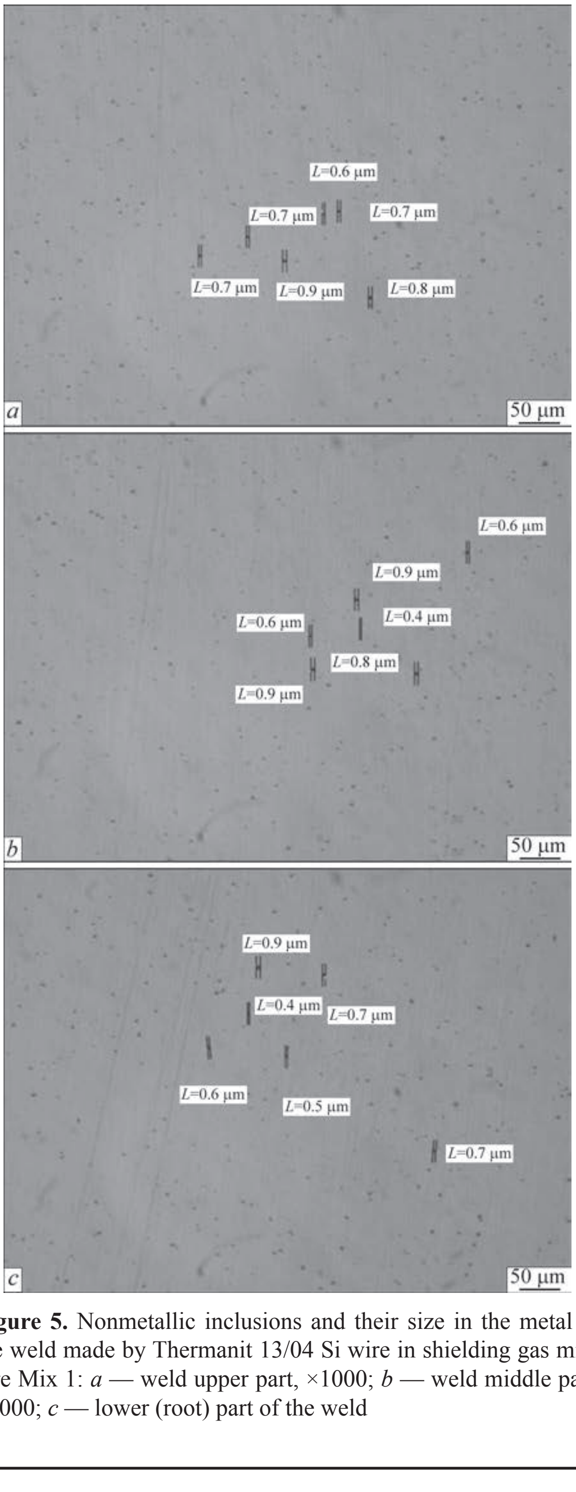

Figure 5. Nonmetallic inclusions and their size in the metal of the weld made by Thermanit 13/04 Si wire in shielding gas mixture Mix 1: *a* — weld upper part, ×1000; *b* — weld middle part, ×1000; *c* — lower (root) part of the weld

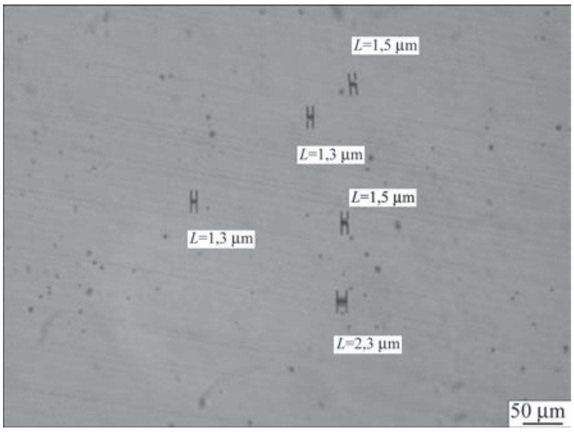

Figure 6. Nonmetallic inclusions and their size in the metal of the weld made by FOX CN 13/4 electrodes

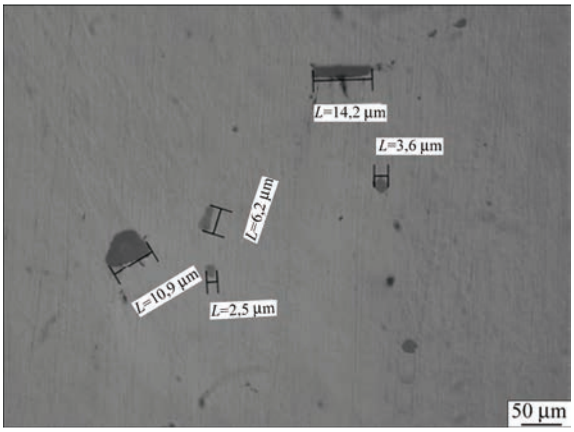

Figure 7. Nonmetallic inclusions and their size in CA-6 NM steel

resulting from the process of welding and heat treatment. Macrosection of the full cross-section of the welded joint after heat treatment is shown in Figure 4.

For microanalysis, microsections were cut out of the welded joints after heat treatment, to study the microstructure.

Microstructures of the weld, HAZ and base metal were investigated.

As one can see from the given images in Figure 5, distribution of nonmetallic inclusions in the weld metal is rather uniform. They are isolated and fine oxides and silicates of 0.5–0.9 μm size. For comparison, Figure 6 shows nonmetallic inclusions in the metal of the weld, made by manual arc welding by FOX CN 13/14 electrodes (BOHLER), which are oxides and silicates of 1.3–2.3 μm size.

Nonmetallic inclusions in the base metal of CA-6NM steel shown in Figure 7, are individual oxides of 1.0–2.5 μm size and oxysulphides of 4–15 μm size.

Structural features of different areas of the welded joint of CA-6NM steel are considered in the condition after welding and tempering at 600 °C for four hours. The weld metal in the upper, middle and lower parts has bainitic-martensitic structure. HAZ structure of CA-6NM steel in the upper, medium and lower parts consists of bainite and martensite with inclusions of grain-boundary ferrite. Base metal structure at a distance from the weld is bainitic-martensitic with precipitates of grain-boundary ferrite. Hardness distribution in the welded joint of CA-6NM steel in the condition after heat-treatment is shown in Figure 8.

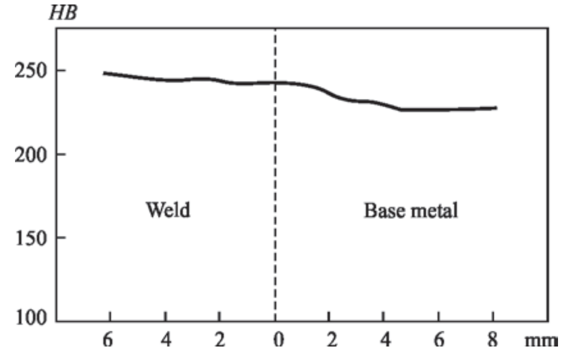

Figure 8. Hardness distribution in the welded joint of CA-6NM steel

Thus, proceeding from the conducted metallographic investigations it was shown that in the metal of the weld deposited by the mechanized process in gas mixture Mix 1 by Thermanit 13/04 Si wire such defects as pores, lacks of penetration, slag inclusions or cracks were absent. It was also shown that the nature of nonmetallic inclusion distribution in the deposited metal in welding in Mix 1 mixture is uniform, compared to the metal deposited with FOX CN 13/4 electrodes. Here, the size of the inclusions is smaller, which has a positive impact on the weld mechanical properties. The weld metal structure is rather homogeneous, it consists of bainite and martensite, which completely corresponds to this class of materials. In the condition after tempering at 600 °C for four hours the weld metal hardness is in the range of 240–250 *HB*. The HAZ structure is characteristic for CA-6NM steel (bainite + martensite) with individual precipitates of grain-boundary ferrite and its hardness is in the range of 230–240 *HB*. The hardness of weld and HAZ metal meets the requirements to welded joints of CA-6NM steel.

Results of the performed investigations were used for certification of the proposed technology of mechanized welding of CA-6NM steel in shielding gas mixture Mix 1. Certification showed the real possibility of application of this technology for welding and rewelding the casting defects in the parts and components of hydroturbine equipment.

CONCLUSIONS

Weldability of CA-6NM martensitic steel was studied and basic technology was developed of its mechanized welding in a mixture of shielding gases, in keeping with the requirements to manufacturing critical parts and components of hydroturbine equipment, as well as rewelding the casting defects. In keeping with the steel strength level, 1.2 mm solid welding wire Thermanit 13/04 Si to EN 12072/G 134 (Germany) and one of the variants of shielding mixture Mix 1 (82 % Ar + 18 % CO_2) were selected and comprehensively studied. The rationality of application of preheating and concurrent heating up to the temperature of 150–200 °C and performance of postweld heat treatment – tempering at the temperature of 600 °C for welded joints of CA-6NM chromium steel was substantiated. The developed technology of MIG welding allows a significant improvement of technological strength and mechanical properties of welded joints by 30–35 % of the level of requirements to the values for base metal of CA-6NM chromium steel. Technology certification was conducted, and recommendations were developed as to its application in production at "Ukrainian Energy Machines" JSC.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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