DEVELOPMENT OF FORGE-WELDED COMBINED MEDIUM-PRESSURE ROTOR FOR 325 MW STEAM TURBINE

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A forge-welded medium pressure rotor for 325 MW steam turbine is described, which is made from 20Kh3MVFA steel (high-temperature operation conditions) and 25Kh2NMFA steel (low-temperature conditions). Welding consumables were selected, and technology of mechanized submerged-arc welding of joints of 25Kh2NMFA + EI 415 steels was developed and certified. Physico-mechanical properties of welded joint metal in the condition after high-temperature tempering in the case of application of both local and imported welding consumables were assessed.

Keywords: *submerged-arc welding, low-alloyed steel, thermal power engineering, steam turbine, rotor, combined welded joint, welding consumables, mechanical properties of joints*

A tendency to design and manufacture powerful steam turbines with welded combined rotor operating in high- and low-temperature mode has emerged in turbine construction over the recent years [1, 2]. The rotors are made of dissimilar structural materials for cylinder operation at high pressure (HPC), medium pressure (MPC) and low pressure (LPC). A feature of making combined rotor joints is the possibility of development of the processes of carbon and alloying element diffusion in the fusion zone of dissimilar steels that essentially influences formation of the structure and service properties of welded joints. In addition, there is a rather complicated issue of postweld heat treatment of such combined joints, as it should be performed for each of the welded steels in different temperature ranges.

OJSC «Turboatom» designed a forge-welded combined MPC rotor for 325 MW steam turbine (Figure 1). Part of the rotor operating in high-temperature mode (stage *1–11*) should be made of EI 415 steel (20Kh3MVFA), and for stages *12–16* operating in the low-temperature mode application of 25Kh2NMFA steel is envisaged. Proposed design of combined MPC rotor also allows elimination of application of nozzle disks in low-pressure stages. Putting the developed design into production requires development of the technological process of manufacturing the forge-welded combined rotor. Therefore, the purpose of this work was selection of welding consumables and development of submerged-arc welding technology ensuring the quality and required service properties of welded joints of the developed combined rotor.

Standard technology of welding LPC rotor of 325 MW turbine, accepted in the plant, envisages welding 25Kh2NMFA steel with Sv-08KhN2GMYu wire (GOST 2246–70) using fused flux AN-17M (GOST 9087–81). Considering the critical shortage of applied wire in Ukraine (produced in RF by special order), as well as stopping fused flux production in the near future, «Turboatom» took a decision on application of imported welding consumables. Conducted marketing studies showed that it is the most rational to select instead of local welding consumables welding wire Union S 3 NiMoCr (ISO 26304) in combination with agglomerated flux UV420TT (EN 760), which are produced by Boehler-Thyssen (Austria, Germany). Selected wire composition, compared to Sv-08KhN2GMYu wire, is given in Table 1.

Fluoride-basic flux UV 420 TT contains the following components, wt.%: (SiO_2 + TiO_2) — 15; (CaO + MnO) — 35; (Al_2O_3 + MnO) — 21; CaF_2 — 25, with basicity of 2.5 to Bonishevskii [3]. During preliminary experiments it was established that concentration of diffusible hydrogen H_{dif} is not more than 1 $cm^3/100$ g of deposited metal at determination by alcohol test [4]. Content of residual gases in weld metal was determined by the method of sample melting in a flow of high purity carrier-gas (helium). It is established that application of Union S 3 NiMoCr wire in combination with UV 420 TT flux ensures

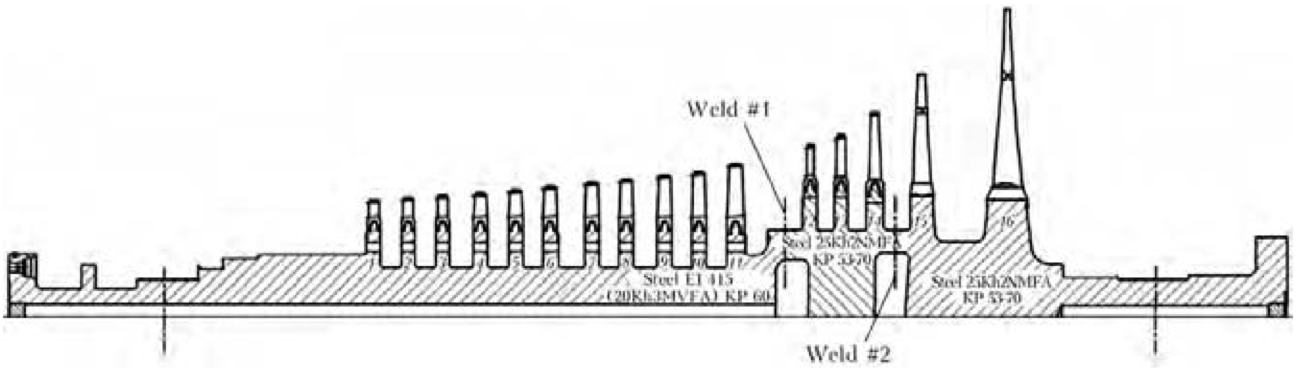

Figure 1. Sketch of longitudinal section of MPC welded rotor of 325 MW turbine.

0.0076–0.016 [N], 0.029–0.034 % [O] and 2.0–2.2 cm^3 [H] per 100 g of deposited metal in the weld. Considering positive results of preliminary studies, work on development and certification of the technology of welding, a combined joint of 25Kh2NMFA + EI 415 steels with application of both imported and local consumables was performed.

Certification of the technological process of welding combined joints of 25Kh2NMFA + EI 415 steels was conducted in keeping with DSTU 3951–2000 (ISO 9956:1995) that envisaged preparation and welding of a full-scale reference butt welded joint (outer diameter of 940 mm, base metal thickness of 95 mm) under the conditions of real production, according to preliminary welding procedure specification (pWPS) provided by the manufacturer.

As 25Kh2NMFA and EI 415 steels belong to the same structural class (Table 2), in order to make a reference combined welded joint of these steels, the same technological process was selected as that used for similar welded joints of 25Kh2NMFA steel. Combinations of local welding consumables, welding modes and postweld heat treatment parameters applied in the standard technology of welding similar joints of 25Kh2NMFA steel allow producing metal of the weld and welded joints with physico-mechanical characteristics satisfying the specification requirements (Table 3, lower line). These values were considered as specification requirements also to metal of combined welded joint of 25Kh2NMFA + EI 415 steels.

In keeping with the accepted technological process, welding of reference joint of 25Kh2NMFA + EI 415 steels was performed with U-shaped groove 26 mm wide with programmed control of bead arrangement with two beads in a layer at reverse polarity direct current. Pre-

Table 1. Content of chemical elements in wires for rotor steel welding and in weld metal of reference welded joint of 25Kh2NMFA + EI 415 steel, wt.%

Object of study	C	Si	Mn	Ni	Cr	Mo	Al	S	P
Sv-08KhN2GMYu wire (GOST 2246–70)	0.06–0.11	0.25–0.55	1.00–1.40	2.00–2.50	0.70–1.10	0.40–0.65	0.06–0.18	≤0.03	≤0.03
Sv-08KhN2GMYu wire[1]	0.08	0.32	1.09	2.15	0.87	0.47	0.11	0.012	0.015
Union S 3 NiMoCr wire (ISO 26304)	≤0.15	≤0.40	1.20–1.90	1.50–2.25	0.20–0.65	0.30–0.80	–	≤0.018	≤0.018
Union S 3 NiMoCr wire[1]	0.14	0.05	1.84	2.06	0.35	0.35	–	0.011	0.013
Weld metal when Sv-08KhN2GMYu wire is used	0.032	0.44	0.66	2.14	0.86	0.52	–	0.012	0.033
Weld metal when Union S 3 NiMoCr wire is used	0.088	0.319	1.61	2.31	0.44	0.60	–	0.009	0.022
Union S 3 NiMoCr wire[2]	0.09±0.01	0.3±0.1	1.3±0.1	2.0±0.1	0.60±0.05	0.5±0.1	–	min	min

[1]Wire actually used in the work.
[2]Requirement to chemical element composition in imported wire.

Table 2. Chemical element content in rotor steels, wt.%

Steel grade	C	Si	Mn	S	P	Cr
25Kh2NMFA (TU 108-995–81)	0.23–0.27	0.17–0.35	0.40–0.70	≤0.015	≤0.015	1.80–2.20
25Kh2NMFA[1]	0.27	0.28	0.50	0.010	0.014	2.10
20Kh3MVFA (TU 108-1029–81)	0.17–0.24	≤0.40	0.25–0.60	≤0.022	≤0.025	2.40–3.30
20Kh3MVFA[1]	0.22	0.27	0.32	0.010	0.012	3.14

Table 2 (cont)

Steel grade	Mo	V	W	Ni	Cu
25Kh2NMFA (TU 108-995–81)	0.40–0.60	≤0.05 acc. to calc.	–	1.30–1.60	≤0.25
25Kh2NMFA[1]	0.42	0.05	–	1.40	0.14
20Kh3MVFA (TU 108-1029–81)	0.35–0.55	0.45–0.70	0.30–0.50	≤0.50	≤0.25
20Kh3MVFA[1]	0.40	0.66	0.40	0.30	0.12

[1]Steel actually used in the work.

heating and concurrent heating of the reference welded joint up to the temperature of 350 °C was performed to prevent cold cracking.

In order to reduce material and labour content of investigations, it was planned to fill the groove of reference combined joint with local consumables to half of its height, and the second half — with imported consumables (Figure 2). Therefore, the weld lower part was made up to half of groove height with application of welding wire Sv-08KhN2GMYu of 2 mm diameter in combination with AN-17M flux. Filling of the weld upper part was conducted with application of Union S 3 NiMoCr wire of 2.5 mm diameter in combination with UV 420 TT flux. Welding was performed in the following mode using both the combinations of welding consumables: welding current 380–400 A; arc voltage 36–40 V; welding speed 19–22 m/h. Finished welded joint was subjected to high tempering at the temperature of 630 °C for 40 h. After that the welded joint was cut into templates for preparation of samples by certification testing program.

Templates, transverse relative to the weld, allowed making samples for testing welded joint metal, including all the possible combinations of base and weld metal, for tension, impact and static bending. In samples of type II to GOST 6996–66 for room temperature tensile testing and type 2k to GOST 9651–73 for tensile testing at the temperature of 350 °C the fusion line was in the middle of sample working part (Figure 3).

Table 3. Results of testing metal of combined welded joint of 25Kh2NMFA + EI 415 steels for static tension (by the results of three tests)*

Object of study	Mechanical characteristics at testing temperature, °C							
	20				350			
	σ_t, MPa	$\sigma_{0.2}$, MPa	δ_5, %	ψ, %	σ_t, MPa	$\sigma_{0.2}$, MPa	δ_5, %	ψ, %
Weld metal (Sv-08KhN2GMYu)	607.2	507	26.2	67.2	539.9	424	19.3	61.2
Weld metal (Union S 3 NiMoCr)	741	503.1	22.9	61.2	675.4	472.2	22.2	60.5
Welded joint metal:								
weld 1 — EI 415 steel	623.6	–	–	67.4	540.6	–	–	61.3
weld 1 — 25Kh2NMFA steel	614.1	–	–	65.3	537.9	–	–	62.5
weld 2 — EI 415 steel	739.1	–	–	61	617.2	–	–	56.3
weld 2 — 25Kh2NMFA steel	709.3	–	–	66.6	611.7	–	–	64.0

*Requirements to short-term mechanical properties of metal of rotor steel welded joints after high-temperature tempering: for 20 °C: σ_t > 590 MPa, $\sigma_{0.2}$ > 470 MPa, δ_5 > 14 %, ψ > 40 %; for 350 °C: σ_t > 530 MPa, $\sigma_{0.2}$ > 400 MPa, δ_5 > 14 %, ψ > 40 %.

The following designations were used in Figure 3: *1* — zones of variable chemical composition; *2*, *3* — samples of type II and type 2k for testing at normal and increased temperature of metal of welded joint of weld (Union S 3 NiMoCr wire) — steel 25Kh2NMFA; *4*, *5* — weld (Sv-08KhN2GMYu wire) — 25Kh2NMFA steel; *6*, *7* — weld (Union S 3 NiMoCr wire) — EI 415 steel; *8*, *9* — weld (Sv-08KhN2GMYu wire) — EI 415 steel, respectively. In samples of type IX to GOST 6996–66 for impact bend testing the sharp notch was made in weld metal, along the fusion line and along HAZ metal on each of the steels at 1.0–1.5 mm distance from the fusion line (Figure 4). The following designations are used in Figure 4: *1*, *2* — weld zones not subjected to examination (location shown in Figure 3); *3*, *4* — samples for determination of *KCV* of metal of weld made with application of imported and local consumables; *5*, *6* — samples for determination of *KCV* of metal of welded joint with a weld made with imported consumable application; *7*, *8* — with application of local consumables, respectively; *9*, *10* — samples for determination of *KCV* of HAZ metal of welded joint with a weld made with application of imported consumables; *11*, *12* — with application of local consumables, respectively. In samples of type XXVII to GOST 6996–66 for static bend testing of welded joint metal, weld axis was located in sample mid-length. Samples of type II to GOST 6996–66 and type 2k to GOST 9651–73 for tensile testing of weld metal at the temperature of 20 and 350 °C, respectively, were made from templates longitudinal relative to the weld.

As is seen from tensile testing results given in Table 3, strength properties and ductility characteristics of the metal of weld and welded joint quite well satisfy the requirements made in welding with both local and imported welding consumables. Weld metal produced with application of imported consumables is stronger than weld metal produced using local welding consumables. At room temperature its ultimate strength is 22 % higher at the same yield point. At the temperature of 350 °C, σ_t value of weld made with imported welding consumables, rises by 25.1 %, and yield point becomes higher by 11.4 %.

It is established that at any testing temperature the joints welded with application of local welding consumables fail in the weld metal. Joints, welded with application of imported consumables, failed in the weld metal only at the temperature of 20 °C and just in samples including base metal — EI 415 steel (see Figure 3, *6* and *7*). In all the other cases joints, welded with

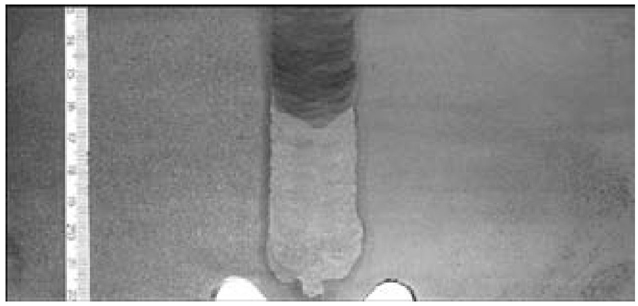

Figure 2. Macrostructure of metal of combined welded joint of EI 415 and 25Kh2NMFA steels (on the right)

application of imported welding consumables, fail in the base metal at 4 mm distance from the fusion line.

Static bend testing showed that bend angle of combined welded joints of 25Kh2NMFA + EI 415 steels is not less than 150°, irrespective of welding consumable combination.

Results of impact bend testing were used to plot graphs of temperature dependence of metal impact toughness *KCV* (Figure 5). The impact toughness value accepted as the criterion for comparative evaluation was *KCV* = 59 J/cm^2, which, according to the current specifications, is the minimum admissible value for any region of similar welded joints of 25Kh2NMFA steel made by the standard technology. As is seen, cold resistance of 25Kh2NMFA + EI 415 welded joint is determined by cold resistance of fusion zone of the weld and EI 415 steel, irrespective of selected welding consumables. At graphic determination, critical brittleness temperature of fusion zone of weld with EI 415 steel is equal to 66 °C in the case of application of local welding consumables (notch in the fusion line). In the case of application of imported welding consumables critical temperature T_{cr} of the zone of weld fusion

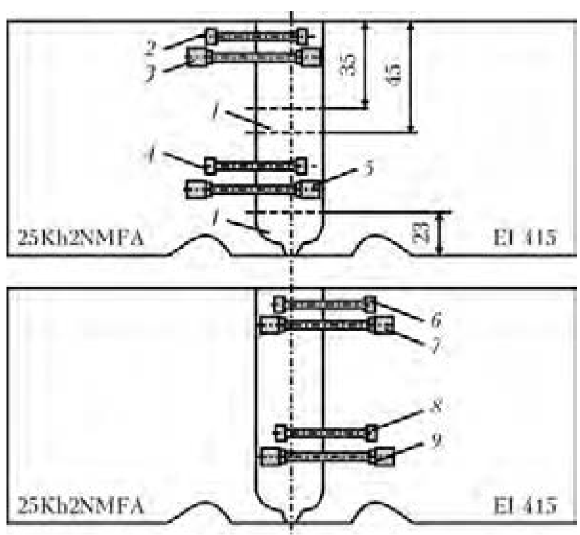

Figure 3. Location of weld zones by cross-sectional height of combined welded joint, and schematic of cutting out samples for tensile testing (for designations see the text)

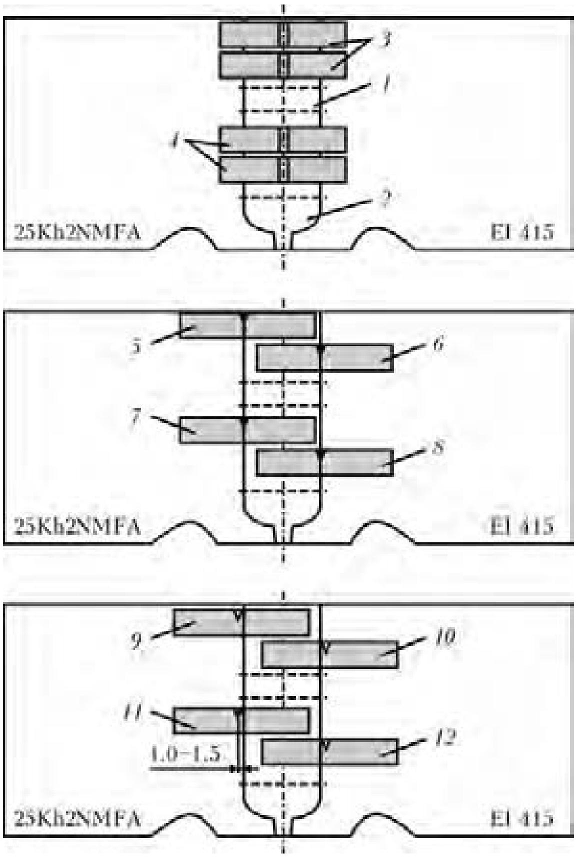

Figure 4. Schematic of cutting out samples of type IX to GOST 6996–66 for impact bend testing (for designations see the text)

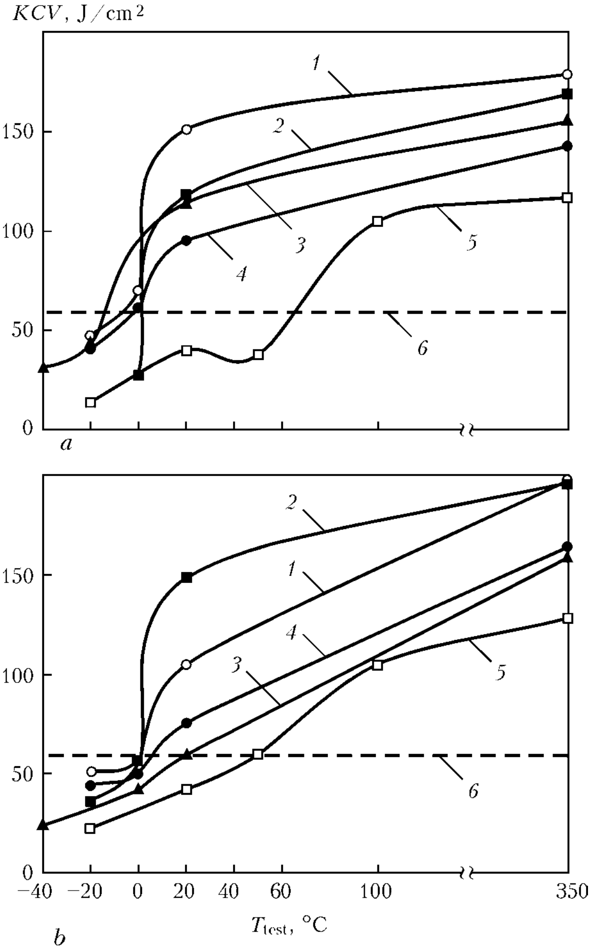

Figure 5. Temperature dependence of impact toughness of metal of combined welded joint of 25Kh2NMFA + EI 415 steels with weld made with local (*a*) and imported (*b*) welding consumables: *1*, *2* — notch in HAZ of 25Kh2NMFA + EI 415 steels, respectively; *3* — notch in Sv-08KhN2GMYu (*a*) and Union S 3 NiMoCr (*b*) weld; *4*, *5* — notch along the line of fusion with 25Kh2NMFA + EI 415 steels, respectively; *6* — RS requirement

with EI 415 steel is equal to 50 °C. For comparison: T_{cr} of the zone of weld fusion with steel 25Kh2NMFA is equal to −2 and 6 °C in the cases of application of local and imported welding consumables, respectively.

Distribution of metal hardness across the reference combined welded joint is shown in Figure 6. As is seen from the graph, the hardness of metal, deposited with application of imported welding consumables, is on average 30 units higher than that of weld metal made with local welding consumables. Average hardness of the zone of weld fusion with EI 415 steel is equal to 276, that is by 40 units higher than that of the zone of fusion with 25Kh2NMFA steel.

Obtained results show that the temperature of postweld tempering, optimum for the joint of weld with 25Kh2NMFA steel, is insufficient to reduce the hardness in the overheating zone of EI 415 steel. Increased hardness of the zone of fusion of the weld with EI 415 steel and HAZ on this steel is logically responsible for lower values of impact toughness of the metal of welded

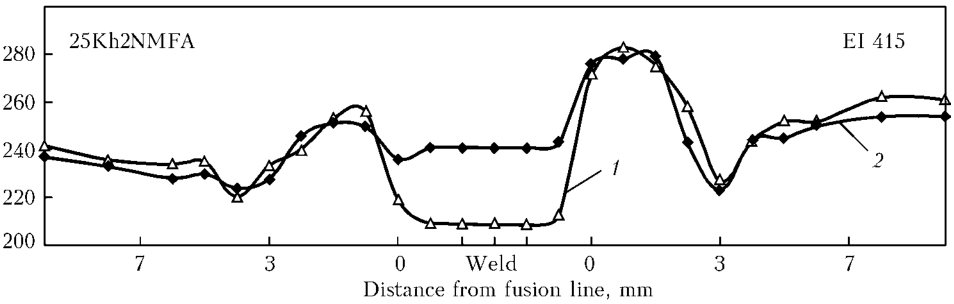

Figure 6. Hardness distribution of metal across the combined welded joint of 25Kh2NMFA + EI 415 steels: *1*, *2* — welded joint with weld made with Sv-08KhN2GMYu and Union S 3 NiMoCr wires, respectively

joint of the weld with EI 415 steel, irrespective of the selected welding consumables.

At impact bend testing it was also found that local welding consumables provide somewhat higher values of weld metal impact toughness at room and below zero temperatures, than imported welding consumables. At the temperature of 350 °C weld metal impact toughness values are quite close for both combinations of welding consumables. T_{cr} value of weld metal is equal to −14 and 20 °C at application of local and imported welding consumables, respectively.

Results of tensile and impact bend testing of weld metal at application of imported welding consumables, compared to the local consumables, are attributable to too high level of alloying of Union S 3 NiMoCr welding wire by carbon and particuarly, manganese (see Table 1). In this connection for practical application of the above welding wire in rotor welding, the requirement of ensuring its composition within ISO 26304 specification, but in narrower ranges was coordinated with the supplier company (see Table 1, lower line).

Proceeding from the results of the performed work on certification of the technological process of welding combined MPC rotor of K-325 steam turbine, two imported welding consumables (Union S 3 NiMoCr wire in combination with UV 420 TT flux) can be selected instead of local consumables (Sv-08KhN2GMYu wire in combination with AN-17M fused flux) for mechanized welding of joints of 25Kh2NMFA + EI 415 steels. Imported welding consumables ensure good welding-technological properties, required composition and minimum content of impurities and gases in weld metal. To ensure high service properties of welded joints of MPC rotors, welding wire Union S 3 NiMoCr should be supplied to ISO 26304-A-S-55-4 requirements. Imported wire should have a more strictly specified composition within ISO 26304-A-S-55-4 specification that will allow bringing its composition closer to local wire composition and ensuring a high impact toughness of weld metal, respectively.

Technical council of OJSC «Turboatom» discussed the performed work on development of forge-welded MPC rotor of 325 MW turbine, and took a decision on suitability of the certified technology for manufacture of combined rotors of steam turbines from 25Kh2NMFA + EI 415 steels. Proceeding from the fact that the weld of the combined joint (see Figure 1, weld 1) will operate at the temperature of about 200 °C, when *KCV* value of metal of the zone of fusion of weld with EI 415 steel is higher than 100 J/cm^2 (see Figure 5), imported welding consumables, ensuring the required brittle fracture resistance of weld metal ($T_{cr} \leq 20$ °C), were recognized to be acceptable for producing welded joint of 25Kh2NMFA + EI 415 steels.

CONCLUSIONS

1. Forge-welded combined rotor of MPC of 325 MW steam turbine was designed. Developed design allows elimination of nozzle discs in low pressure stages.

2. Technology of mechanized submerged-arc welding of a combined joint of MPC rotor from 25Kh2NMFA + EI 415 steels was developed and certified.

3. It is recommended to apply for mechanized welding imported welding wire Union S 3 NiMoCr (ISO 26304-A-S-55-4) in combination with agglomerated flux (UV 420 TT (EN 760) of Boehler-Thyssen (Austria, Germany).

4. Mechanized submerged-arc welding with application of the selected imported welding consumables can be applied to manufacture LPC and MPC rotors of powerful steam turbines.

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