doi.org/10.15407/tpwj2017.12.07

IMPROVEMENT OF IMPACT TOUGHNESS OF METAL OF COMBINED WELDED JOINTS OF ALLOYED BAINITE STEELS

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A possible approach in the development of technology of producing combined welded joints of bainite steels was formulated as-applied to critical welded units, based on the purposeful presetting the optimum content of alloying elements and impurities in the base and filler metal within their grade composition according to the standard documents and contributing to improvement of their service characteristics. The comparison of results of experimental investigations obtained within the standard certification of welding technology, allows assuming that the implemented approach is effective. 9 Ref., 2 Tables.

Keywords: *alloyed steel, rotor steel, combined welded joints, welding consumables, chemical composition, submerged arc welding, heat treatment, tempering brittleness, impact toughness*

In the PJSC «Turboatom» the new generation steam turbine K-325-23.5 was manufactured, which meets the modern requirements to reliability, economy and maneuverability [1]. For this turbine a forge-welded combined rotor of medium-pressure cylinder was designed, operating in a high- and low-temperature mode [2]. A part of the rotor operating in the high-temperature mode (1–11 stages) is manufactured of steel EI 415 (20Kh3MVFA). A part of the rotor, operating in a low-temperature mode (12–16 stages) is manufactured of steel 25Kh2NMFA. These steels belong to the same structural class, but differ in the alloying system. In steel EI 415 the nickel content is 2.6 times lower than in 25Kh2NMFA, and the chromium is 1.5 times higher. Moreover, steel EI 415 contains the strong carbide-forming elements: vanadium and tungsten. Due to the mentioned features of alloying, the steel EI 415 has a higher phase stability at elevated temperatures, which determines its selection for manufacture of a rotor section operating in a high-temperature mode.

Earlier, the technology for producing a combined welded joint of steel EI 415 and 25Kh2NMFA (further — joint EI 415 + 25Kh2NMFA) was developed using the wire of grade Union S 3 NiMoCr (type A-S 55 4 according to ISO 26304) in combination with flux of grade UV 420 TT (type SA FB 1 65 DC according to ISO 14174). It is based on the approach, in accordance with which the homogeneous welded joints of steel 25Kh2NMFA are produced: filling the U-shaped groove of a constant width by a multipass submerged arc welding method with preheating the base metal to 350 °C and the postweld high tempering for 40 hours at the.630 °C temperature. However, the results of research certification of this technology showed that the tempering temperature, optimal for the metal of weld fusion zone with steel 25Kh2NMFA appeared to be insufficient to provide the required impact toughness of metal of weld fusion zone with steel EI 415, regardless of the used welding consumables [2]. Thus, at the 20 °C temperature, the average value of *KCV* of weld metal of welded joint steel EI 415 (notch along the fusion zone), was 42 J/cm^2. This value is lower than the required value of impact toughness (≥ 59 J/cm^2) for the metal of homogeneous welded joints of steel 25Kh2NMFA, established by technical documentation on manufacturing the rotors of turbines and a priori widespread for the joints EI 415 + 25Kh2NMFA.

Therefore, the further aim was to find technological capabilities for increasing *KCV* of metal of the fusion zone on steel EI 415 to the required value. Moreover, it is desirable to preserve the process of welding steels 25Kh2NMFA and EI 415 between each other as a homogeneous joint, which is characterized by simplicity (without preliminary surfacing to the edge of the base metal, intermediate heat treatment, etc.). To achieve this aim, the analysis of the previously obtained results of research certification of the technology of welding the joints EI 415 + 25Kh2NMFA was carried out [2] in comparison with specific welding conditions of the certified reference welded joint (RWJ) and the known regularities of changing mechanical properties during tempering of alloyed steels.

The results of investigations [3–6] allow assuming that the most obvious cause for the lowered impact toughness of the fusion zone on steel EI 415 is a tempering brittleness. It is known about negative influence of harmful impurities, especially phosphorus, on the tendency of low- and medium-alloyed steels to embrittlement. In particular, the harmful effect of phosphorus, introduced together with manganese at the content of latter being 1 % and higher, sharply manifests itself. Similarly to manganese, silicon also increases the tendency of steels to tempering brittleness. Moreover, the increase in silicon content expands the dangerous range towards the high temperatures.

It was generalized, that for the most considered steels, for developing the phenomena of tempering brittleness the temperature range of 250–650 °C can be considered [4–6]. Within this range, there are temperatures of preliminary and concurrent preheating, in which the welding of rotor steels is usually carried out in order to produce the minimum content of products of the diffusion-free decay of austenite in the HAZ metal and to prevent the delayed fracture of welded joints.

During tempering of welded joints of rotor steels, it is also impossible to avoid their staying in a dangerous temperature range, as far as for thick-walled large-sized welded units after holding at the tempering temperature, only slow furnace cooling is possible. Therefore, in principle, for any area of welded joint of any rotor steel after heat treatment some embrittlement and a corresponding reduction in impact toughness is inevitable as compared to the level which could be achievable at the accelerated cooling of rotors after tempering.

In case of carrying out tempering of welded joint of rotor steel at the optimum temperature (above the temperature range of embrittlement of this steel), the final stage of embrittlement of welded joint metal turns to be low, since it is determined only by the holding time in the dangerous range when the product is subjected to the furnace cooling. This is confirmed by the practice of producing homogeneous welded joints of steel 25Kh2NMFA, after the tempering of which at 630 °C during 40 h, the requirement to impact toughness KCV ($\geq$ 59 J/cm^2) of the fusion zone metal is provided with a noticeable margin. At the same time, for steel EI 415 the lower limit of the recommended tempering temperatures according to TS 108-1029–81 is 660 °C. Therefore, it can be assumed that the accepted temperature of tempering the joints EI 415 + 25Kh2NMFA (630 °C) enters the dangerous range for steel EI 415. In this case, the metal of fusion zone on steel EI 415 is in the dangerous range at all the stages of producing welded joint (preliminary and concurrent preheating during welding, transportation to the furnace, heating, holding at the temperature of high tempering and furnace cooling). Then, the lowered values of impact toughness of the metal of fusion zone on steel EI 415 in the combined joint and also revealed by mechanical tests, are, apparently, the logical result of its many-hour holding in a wide range of temperatures, where in steel EI 415 the totality of phenomena of tempering embrittlement of a different nature can develop.

It is possible to eliminate the embrittlement of steel EI 415 and the metal of all the zones of its welded joint only by tempering above the dangerous range, i.e. at the temperatures recommended for it ($\geq$ 660 °C). But the carrying out of the postweld tempering of joints EI 415 + 25Kh2NMFA at the temperatures $\geq$ 660 °C is unacceptable, since it leads to weakening the steel 25Kh2NMFA [6], the tempering temperature of which is 630–650 °C according to TS 108-995–81. If there is no possibility to increase the temperature of postweld tempering of the combined rotor, it is only possible to influence other factors determining the tendency of steel EI 415 to tempering embrittlement, its chemical composition and duration of metal staying in the dangerous range.

The features of steel EI 415, selected for manufacturing the high-temperature part of the combined rotor of the steam turbine K-325-23.5 for the Uglegorsk TPS, unlike the steel applied in the previously certified RWJ [2], were a very low phosphorus content and the content of silicon, reduced to the minimum (Table 1).

The duration of metal staying of combined welded joint in the most dangerous area in the range of embrittlement of steel EI 415 was reduced by establishment of rigid requirements to the temperature of concurrent heating, control of the temperature of base metal during welding in the vicinity of the groove and its active regulation due to change in the power of heating device to prevent overheating. As a rule, the lower limit of the temperature of preliminary and concurrent preheating of the combined welded joint EI 415 + 25Kh2NMFA as 350 °C is appointed. At the positive ambient temperature in the course of continuous automatic welding of circumferential joint, the temperature of the metal as a result of automatic heating begins to exceed the preset temperature rather soon. In view of the notion of the required temperature of preheating the steel EI 415 (400–500 °C), which has long been formed in the practice of welding the homogeneous joints of this steel [7, 8], the effect of self-heating of metal of the joint EI 415 + 25Kh2NMFA was not still considered undesirable.

Table 1. Content of elements in steel EI 415 (TS 108-1029–81) in the composition of RWJ EI 415 + 25Kh2NMFA and in metal of their welds, wt.%

Object of control	C	Si	Mn	Ni	Cu	Cr
Steel EI 415 according to TS 108-1029–81	0.17–0.24	≤ 0.40	0.25–0.60	≤ 0.50	≤ 0.25	2.40–3.30
Steel EI 415 in RWJ, certified in 2011 [2]	0.22	0.27	0.32	0.30	0.12	3.14
Steel EI 415 in RWJ, certified in 2014	0.23	0.059	0.35	0.38	0.15	2.71
Weld metal in RWJ, certified in 2011 [2]	0.088	0.32	1.61	2.31	–	0.44
Weld metal in RWJ, certified in 2014	0.088	0.37	1.41	2.31	–	0.72

Table 1 (cont.)

Object of control	Mo	V	W	S	P
Steel EI 415 according to TS 108-1029–81	0.35–0.55	0.45–0.70	0.30–0.50	≤ 0.022	≤ 0.025
Steel EI 415 in RWJ, certified in 2011 [2]	0.40	0.66	0.40	0.010	0.012
Steel EI 415 in RWJ, certified in 2014	0.41	0.50	0.32	0.003	0.005
Weld metal in RWJ, certified in 2011 [2]	0.60	–	–	0.009	0.022
Weld metal in RWJ, certified in 2014	0.50	0.018	–	0.012	0.017

Therefore, in the process of filling the deep groove, the temperature of the .concurrent preheating of weld metal and the areas of the base metal adjacent to it could amount to 400–450 °C or higher for a long time. This mainly concerns the full-scale model of the rotor, containing RWJ EI 415 + 25Kh2NMFA, on which the certified welding process is reproduced. The differences in values of weight and dimensions and heat capacity of the rotor and its full-scale model contribute to a particularly strong overheating of the latter (up to the maximum values of the above-mentioned temperature range).

Meanwhile, from the point of view of the known facts, holding the metal of the joint welded of alloyed steels in this range can lead to undesirable consequences. At first, it enters the range of reversible tempering brittleness of steels at 375–575 °C [5]. Secondly, due to excessively low cooling rate $w_{6/5}$ and elevated temperature of austenite decay, the unfavorable changes in composition of the decay products can occur. The γ-phase is stabilized and the content of residual austenite grows. Except of bainite and martensite, ferrite may also appear [9]. This means nothing more than an increase in the degree of microchemical (phase) heterogeneity of metal of the overheating area and it adversely affects its mechanical properties and tendency to delayed fracture.

Therefore, in the scopes of production certification of the technology (before welding the rotor for the Uglegorsk TPS), in the course of welding of RWJ EI 415 + 25Kh2NMFA, the measurement of temperature of the concurrent preheating was combined with the change in the power of gas heater flame (as required). Due to regulation of gas heater power, all the values of temperature of preliminary and concurrent heating of the RWJ metal, measured during multipass welding, were in the range of 316–365 °C.

Thus, all the changes in the previously developed technology of welding the joints EI 415 + 25Kh2NMFA consisted only in the mentioned limitation in top of the temperature range of the concurrent preheating and differences in the chemical composition of base metal of steel EI 415 in the certifying RWJ presented in Table 1. The other conditions and parameters of welding technology, methods of investigation of mechanical properties of RWJ metal, schemes of cutting out the specimens for impact bending tests remained unchanged and described in detail in the work [2].

The results of evaluation of impact toughness of the RWJ metal sections produced during the production certification of changed welding technology are shown in Table 2 in comparison with the similar results of research certification [2]. The combined effect of change in the temperature of concurrent preheating and the content of silicon and phosphorus in the base metal of steel EI 415 appeared to be quite effective. The average value of impact toughness of the welded joint metal (notch along the fusion zone of weld and steel EI 415) increased almost twice. The difference in the content of phosphorus and especially manganese in the weld metal of the RWJ, certified according to the changed technology, can be considered negligible as compared to the similar values according to the research certification results (see Table 1). Then the marked increase in the average value of *KCV* of the weld metal (notch in weld height) by 68 % can be explained almost exclusively due to the favorable effect of changed thermal mode of the multipass welding.

The obtained values of *KCV* with a reliable margin meet the requirement to impact toughness (≥ 59 J/cm^2) of metal of the combined welded joint of rotor steels at a room temperature. All the other characteristics of mechanical properties of any section of RWJ EI 415 + 25Kh2NMFA, produced applying the changed technology, also meet the specified requirements.

As one of the results of the gained experience of welding the combined rotor steels, it is appropriate to note the role and generalize the approach realized above, which, in a number of cases, can apparently be very productive both in independent application as well as in combination with other technological measures. This approach, according to which the search for reserves to approximate the controlled characteristics to the required value is carried out in the ranges of the content of alloying elements and impurities in steels, admitted by regulatory documents [6]. This way can be the most rational for improvement of the technology for producing the combined welded joints of two bainite steels, for example, when the ranges of optimum temperatures of their tempering do not match and it is impossible to provide meeting the separate characteristics to the required values applying postweld tempering, and the degree of discrepancy is low. The realization of the mentioned approach should consist in the fact that the postweld tempering of the combined joint «steel 1 + weld + steel 2» is carried out at the temperature, guaranteeing the proper mechanical properties of all the areas of welded joint of steel 1. Moreover, on the basis of general knowledge about the effect of alloying elements and impurities on the controlled characteristic, the most favorable chemical composition of steel 2 is established (however, within the limits of its standard grade composition) and the coordination of more rigid requirements to the content of one or more elements with the manufacturer of this steel is carried out.

The same may concern the deposited metal, and in this case, special requirements to the content of alloying elements are coordinated with the manufacturer of welding consumables. There is a positive experience of such coordination, during which an enterprise-supplier of the wire of grade Union S 3 NiMoCr expressed its readiness to provide its chemical composition within the welding frames of ISO 26304, but in the required more narrow limits.

Conclusions

1. The technological approach was formulated, which can be useful in improvement of technology for producing combined welded joints of bainite steels. If the postweld tempering of a combined welded joint of the mentioned steels at a temperature higher than the embrittlement range of one of these steels is impossible, it is possible to reduce the tendency to tempering embrittlement and ensure the correspondence of impact toughness of metal of the fusion zone of this steel to the required values by limiting the content of silicon in this steel and (or) manganese in the .scopes of standard graded composition of steel, as well as phosphorus.

2. The preheating of metal of the combined welded joints of steels EI 415 and 25Kh2NMFA to the temperature of 350 °C and preventing its overheating in multipass submerged arc welding above 365 °C (welding at the temperature of the .concurrent preheating considerably lower than that, which was still considered necessary for steel EI 415) has a favorable effect on the impact toughness of the overheating area on steel EI 415.

3. The results of investigations in the frames of the production certification of the technology of submerged arc welding of the combined joint of steels EI 415 and 25Kh2NMFA confirmed the suitability of the certified technology for manufacture of the combined rotor of a medium-pressure cylinder of the steam turbine K-325-23.5 for thermal power stations (TPS).

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Received 22.09.2017