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IMPROVING THE OUTPUT QUALITY OF STEAM TURBINE WELDED ROTORS FOR NUCLEAR POWER PLANTS

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Improving the reliability of welded rotors (under conditions of increasing operating loads) is an urgent task in nuclear power engineering. The solution to this problem was achieved by automatic welding of rotors in optimized welding mode parameters using new welding materials. It resulted in obtaining welded rotors with improved quality characteristics of their output structure and without defects, such as pores and non-metallic inclusions. The austenite grains in the structure of the welded joints became much smaller in size. The new austenite decomposition products in the area of incomplete recrystallization of the heat-affected zone were sorbite and troostite, rather than pearlite, which was obtained during the standard automatic welding process. Thus, automatic welding of 25Х2НМФА steel rotors in optimized modes and the use of new welding materials ensured the production of the welded joints with improved quality characteristics of their output structure, which increased the reliability of rotor operation.

INTRODUCTION

Steam turbine rotors for new NPP power units and for units undergoing modernization were manufactured with an eye to increasing their operating loads. Therefore, the manufacture of welded rotors requires ensuring the high quality of their output structure. Therefore, it is necessary to quantitatively increase power generating capacities that meet the UCTE requirements. This increase will provide realistic conditions for the integration of Ukraine's energy sector into the European energy system.

Steam turbines are designed in accordance to the respective steam parameters. The rotors of the cylinders of steam turbines are one of their most critical components. This is why special requirements are imposed on the manufacture of welded rotors in terms of their reliability in operation.

Welded joints of rotors are characterised by structural, chemical and mechanical heterogeneity (caused by the welding heat), which cannot be completely eliminated after high-temperature tempering.

However, this heterogeneity should be reduced to the lowest possible level. This is what will improve the reliability of welded rotors throughout their service.

The aim of this work is to improve the quality characteristics of the output structure of welded rotors made of 25Х2НМФА steel.

The operating angular velocity of the shaftling of the ‘high-speed’ welded rotor is 3,000 rpm. Welded rotors of this type are used in turbines K-220-44; K-320-23.5; K-500-65; K-500-240; K-750-65; K-325-23.5, *etc*.

Welded rotors with the operating angular velocity of the shaftling of 1,500 rpm are part of the ‘low-speed’ turbines: K-500-60/1500; K-1000-60/1500; K-1100-60/1500-2M *etc*.

Welded rotors are composed of discs, tangs and other elements made of 25Х2НМФА steel, Table 1.

Table 1

Chemical composition of steel 25Х2НМФА

The mass part of the elements, %									
C	Si	Mn	S	P	Cr	Ni	Mo	V	Cu
0.29… 0.36	≤ 0.35	0.40… 0.70	≤ 0.015	≤ 0.015	1.80… 2.20	1.30… 1.60	0.70… 0.60	0.05	≤ 0.25

The yield strength of the output welding blanks made of 25Х2НМФА steel is 471 MPa. To analyse the structure of welded joints made of the above steel. we took into account the output structure of the blanks and the methods used to obtain them. The mechanical properties. structural and chemical heterogeneity are calculated individually with respect to compliance with the regulatory provisions [1-5]. For example. it was taken into account that the spread of indicators shall not exceed 30 units. The critical brittleness temperature is also determined for each of the indicators. The macrostructure of the blanks must be free of cracks. flocks. shrinkage holes. shells. chains and relatively large non-metallic inclusions. as well as non-metallic inclusions in the form of chains. Non-metallic inclusions with a size of 2 to 4 mm in an amount not exceeding 5 pieces are permitted. Non-metallic inclusions up to 1 mm in size are also permitted if such inclusions do not form local clusters and chains. Clusters look like separate locally grouped non-metallic inclusions up to 1 mm in size. in an amount of more than 10 pieces. The distance between inclusions shall not exceed 5 times the length of the largest defect included in such a cluster. The chains are inclusions grouped in a line. up to 2 mm in size in an amount of at least 5 pcs. The distance between such inclusions shall not exceed 3 times the length of the most elongated defect included in the chain. Non-metallic inclusions with a longitudinal dimension of more than 2 mm are considered to be large. Thus. the problem of increasing reliability should be solved by obtaining weld metal joints with improved quality characteristics and without the original non-metallic inclusions.

The reliability of welded rotors is largely limited by the structural-phase state of their metal. In the areas of fusion. overheating and incomplete recrystallization of the heat affected zone (HAZ). structures are formed that can be classified as defective. Let us analyze these structures. Large austenitic grains (3-4 points according to ДСТУ 8972:2019) are formed in the areas of fusion and overheating during welding at regular operating modes [6–10]. In the area of incomplete recrystallization. new austenite decomposition products can form in the form of globularized pearlite [5–7].

Thus. it is advisable to obtain welded joints with as few output defects as possible. as well as with a better structural-phase state.

RESULTS AND DISCUSSION

The solution to the problem of improving the reliability of the welded joint is based on solving two problems: obtaining relatively small austenite grains in the areas of fusion. overheating and normalisation of the heat affected zone; obtaining new austenite decomposition products in the form of sorbite or troostite instead of globularised pearlite in the area of the incomplete recrystallization. It is in these areas of the HAZ of the welded joints the damage occurs which leads to their destruction [5, 8–10].

The automatic welding process was performed using the optimised welding mode parameters taking into consideration the results of the modelling of the temperature mode [5–7]. The modelling of the temperature regime with respect to the molten metal of the weld pool as a liquid phase was first performed under the Navier-Stokes law. and the base metal (solid phase) under the Fourier law. The shape of the weld pool at medium welding mode is close to the hemispherical shape. which made it possible to use the cylindrical coordinate system while modelling the temperature mode [11].

The temperature regime model [7, 11] was updated accordingly.

$$\frac{\partial\xi}{\partial t}+\frac{1}{r}\frac{\partial\psi}{\partial r}\frac{\partial\xi}{\partial z}-\frac{1}{r}\frac{\partial\psi}{\partial z}\frac{\partial\xi}{\partial r}+\frac{1}{r}\frac{\partial\psi}{\partial z}\frac{\xi}{r}=\nu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial\psi}{\partial r}\right)+\frac{\partial^2\xi}{\partial z^2}-\frac{\xi}{r}\right]+q\beta\frac{\partial T}{\partial r}+\nabla'(\bar{J}\times\bar{B}).$$

$$\frac{\partial}{\partial z}\left(\frac{1}{r}\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial r}\right)+\xi=0.$$

$$\frac{\partial T}{\partial t}-\frac{1}{r}\frac{\partial\psi}{\partial z}\frac{\partial T}{\partial r}+\frac{1}{r}\frac{\partial\psi}{\partial r}\frac{\partial T}{\partial z}=\frac{1}{\rho c}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q_k\right].$$

Here r, φ, z – the components of the cylindrical coordinate system; ψ – the flow function of the molten metal in the weld pool; ξ – liquid metal flow velocity field; ν – the kinematic viscosity; q – the acceleration of the gravity force; ∇' – the vector. $\nabla'=\partial/\partial r\cdot\bar{e}_z+\partial/\partial z\cdot\bar{e}_r$; $\nabla'(\bar{J}\times\bar{B})$ – the effect of electromagnetic forces on the dynamics of the molten metal of the weld pool; T – temperature; ρ – density; c – thermal capacity; μ – dynamic viscosity; β – the thermal conductivity coefficient; Q – droplet heat transfer.

In general. the improvement of the automatic welding technology included welding in optimized modes and the use of new welding materials. The proposed welding technology involved the optimized parameters of the welding mode and the use of new welding materials for the manufacture of the pilot model. Thus the lower section of the welded joint was welded under the following operating conditions: current 410…420 A; arc voltage 36…38 V; welding speed 20 m/h. Welding was performed using the Св08Г2С electrode wire. Welding of the main seam was performed at the following modes: current 330…380 A; arc voltage 38…40 V; welding speed 25 m/h. The electrode wire used was Union S3Ni.Mo, type SZ3Ni2.5CrMo, No. EN14295. Welding of the upper section was performed at the following operating modes: current 400…420 A; arc voltage 36…38 V; welding speed 20 m/h. The flux used was UV-420TT. type SAFB165. LC No. EN76. The pre-heating and the concomitant heatng during the welding were 350 °C.

The use of the Galerkin method whilst solving the improved thermal problem ensured the smoothly approximated temperature isotherms. The temperature indicators were compared with the experimental temperature measurements and then put on the thermokinetic diagram of 25Х2НМФА steel. This ensured better output structures in the metal of welded joints.

The manufactured welded joint sample was subjected to a high tempering immediately after welding (T = 630…650 °C, τ = 130 h).

The above-mentioned tempering reduced the concentration of harmful impurities at the boundaries of austenitic grains. which significantly increased the interatomic adhesive forces and thus imparted greater strength to the structure. In the presence of large austenitic grains. the tempering only partially contributes to the increase in interatomic adhesive forces. Thus. the problem of increasing the strength of welded joints is solved only partially.

In general. tempering gives the output grains of the structures formed under the influence of welding heat a shape close to round. without increasing their size. In the presence of relatively small austenitic grains. high tempering has a significant positive effect on increasing the strength at the boundaries of the grains.

In order to analyze the structural-phase state of the welded joint. to detect non-metallic inclusions. and to determine its chemical composition and properties templates were cut out of the pilot model. The use of new welding materials ensured the absence of output defects (which are allowed by regulatory provisions [1–4]) in the seem.

Metallographic studies were performed on the metallographic sections cut from the corresponding sections of the welded joint [6]. The output structure of 25Х2НМФА steel was a tempered lower bainite.

The structure of the seem metal appears as sorbite-troostite mixture with a small amount of small ferrite grains. The structure of the fusion area of the HAZ was also sorbite-troostite mixture with more ferrite grains (*c*. 15 %). The size of austenitic grains in the height of the sample in the fusion area was almost the same. *i.e.* 7-8 points (ДСТУ 8972:2019).

It was taken into account that the size of austenitic grains depends on the heating temperature and on the holding time above the critical point Ac_3. The amount of harmful impurities accumulated on the grain boundaries (which is not completely eliminated even with high tempering of welded joints) depends on these parameters.

The overheating area had predominantly sorbite structure. The size of austenitic grains in the overheating area was 8-9 points. The normalization area had the troostite structure. and the size of the austenite grains was *c*. 7-8 points.

Thus. the improved welding technology used in the manufacture of the rotor for the first time made it possible to solve the problem of reducing the austenitic grains size in the welded joint.

It was the modelling of the temperature regime that allowed us to solve the second problem: to eliminate the formation of large globular pearlite grains. as a product of austenite decomposition. in the area of incomplete recrystallization of the HAZ. It should be noted that the metal in this area is subjected to welding heating in the temperature range limited by the critical points Ac_1–Ac_3. Therefore the formation of pearlite components depends on the heating temperature and the holding time in this temperature range. Tempering helps to increase the shape of pearlite grains and also gives them nearly globular shape. In general it is advisable to prevent the formation of pearlite grains. The presence of pearlite grains significantly reduces the strength of welded joints and contributes to their damageability. The modelling of welding heating made it possible to limit the heating to the critical temperature range. which allowed us to obtain much smaller sorbite or troostite grains as new products of the austenite decomposition.

The mechanical properties of the welded rotor obtained by the improved technology exceeded the normatively recommended values (Table 2).

Table 2

$\sigma_{0.2}$	$\sigma_в$	δ	ψ	KCU	Bend
MPa/mm^2		%		J/cm^2	degree
580	730	21.0	65.5	180	120

CONCLUSIONS

1. It has been established that automatic welding in optimized modes and the use of the new welding materials. has produced a welded joint of a 25Х2НМФА steel rotor with the improved output structure.

2. It was found that the welding in optimized mode parametres made it possible to obtain smaller austenite grains in the areas of fusion. overheating and normalization in the HAZ.

3. It was found that the welding in optimized mode parameters prevents the formation of globular pearlite grains in the area of incomplete recrystallization in the HAZ of the welded joints.

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