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IMPROVEMENT OF WELDING TECHNOLOGY OF HIGH POWER TURBINE ROTOR

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In order to solve the problem of increasing the reliability and increasing the service life of welded joints of rotors of high-power turbines of nuclear and thermal power plants, the technology of their manufacture was improved. The improved technology provided obtaining welded joints of rotors with improved characteristics of their original structure and higher mechanical and physical properties. The given properties were determined by comparing with similar properties that are characteristic of the welded connection of the rotor made according to standard technology. The improvement of the technology involved the modeling of welding heating of manufactured joints, which made it possible to optimize the parameters of the mode of automatic welding of the rotor made of 25Х2НМФА steel. For the first time, the thermal problem was solved as a conjugate one under the conditions of the Navier-Stokes and Fourier laws, which provided the results necessary for increasing the reliability of the rotors, as well as increasing their resource.

INTRODUCTION

The problem of increasing the reliability and increasing the service life of the welded joints of rotors of high-power NPP turbines is gaining increasing relevance. The operational characteristics of the rotors are largely determined by the structural state of the welded joints, the formation of which is provided by welding heating.

Welded joints made of 25Х2НМФА steel (TC 108.1082.82) are characterized by the presence of a coarse-grained austenite structure in the areas of fusion and overheating of their heat-affected zone (HAZ) and globularized pearlite in the area of incomplete recrystallization. These structures can be classified as defective.

Obtaining fine-grained austenite in the areas of fusion, overheating and normalization of the HAZ of welded joints made of 25Х2НМФА steel is a very difficult and at the same time necessary task, which is related to the reliability and service life of welded joints. High tempering does not ensure a sufficiently negative effect of large austenite grains, which reduces the resistance of the metal of welded joints to damage and subsequent destruction under operating conditions.

RESEARCH METHODS AND TECHNIQUES

It is effective to reduce the formation of a coarse-grained austenite structure in the areas of fusion and overheating of the HAZ of welded joints. Such a reduction is achieved by modeling the welding heating of the manufactured joints [1, 2]. It is the determined welding heating that allows you to reduce the duration of fusion, overheating and HAZ normalization in the temperature range of intensive growth of austenite grains.

Thus, the prevention of the formation of a coarse-grained austenite structure is provided by a possible way of improving the welding technology of manufacturing rotors. Improvement of the technology is expedient for increasing the operational characteristics of the manufactured joints. The proposed improvement provided for the use of optimized parameters of the welding mode, which were selected on the basis of numerical data characterizing the welding heating of manufactured joints [2]. Numerical data were obtained by modeling welding heating and used to optimize the parameters of the welding mode of witness samples (Fig. 1) from steel 25Х2НМФА (Tabl. 1). The samples in terms of size, chemical composition and heat treatment corresponded to steel 25Х2НМФА, from which the rotor itself was made.

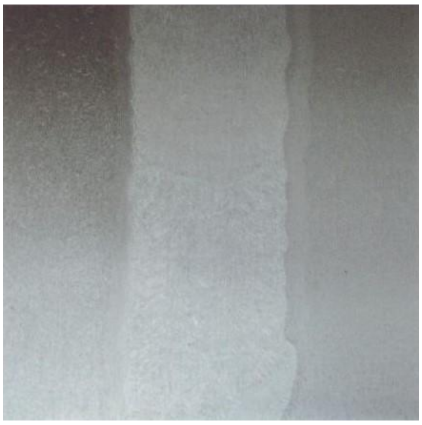

Fig. 1. Macrostructure of the test sample made of steel 25Х2НМФА, ×1.1 [4]

Table 1

Chemical composition of steel 25Х2НМФА

C	Si	Mn	S	P
0.23…0.27	0.17…0.35	0.40…0.70	0.015	0.015

Cr	Ni	Mo	V
1.80…2.20	1.30…1.60	0.40…0.60	0.15

The initial structure of 25Х2НМФА steel consisted of tempered lower bainite and a small amount (7…9 %) of ferrite-carbide mixture (Fig. 2). Critical points of steel: A_{C_1} = 760 °C; A_{C_3} = 820 °C.

Fig. 2. Initial steel structure 25Х2НМФА, ×360

The welding heating was simulated in relation to the manufacture of the experimental sample of the rotor.

FORMULATION OF THE PROBLEM

To optimize the parameters of the automatic welding mode of the witness sample made of 25Х2НМФА steel, a conjugate thermal problem was solved. For the liquid phase (molten metal of the bath), the solution was performed under the conditions of the Navier-Stokes law, and for the solid phase (heat-affected zone and the base metal) under the conditions of the Fourier law.

It was assumed that the calculated shape of the welding bath corresponds to the real shape of the bath and has the shape of a hemisphere.

Mathematical formulation of the problem

$$\frac{\partial \vec{v}}{\partial t} = -(\vec{v} \cdot \nabla)\vec{v} + \nu\Delta\vec{v} - \frac{1}{\rho}\Delta p + \vec{f}, \quad \nabla\vec{v} = 0, \qquad (1)$$

where ∇ – the Nabla operator; Δ – the Laplace operator; t – time; ν – the coefficient of kinematic viscosity; ρ – density; p – pressure; $\nabla\vec{v} = (v^1 \ldots v^n)$ – vector field of velocities of the liquid metal of the bath; $\vec{f}$ – the vector field of mass forces. The unknowns p and ν are functions of time t and coordinates $x \in \Omega$.

The system of Navier-Stokes equations was supplemented with boundary and initial conditions

$$\nabla\vec{v}|_{\partial\Omega} = 0, \quad \nabla\vec{v}|_{t=0} = 0. \qquad (2)$$

At zero values of the velocity vector (the beginning of the primary crystallization process), the temperatures were determined by solving the Fourier equations. Let's write it down

$$\begin{cases} \text{In liquid phase} \\ c\rho\frac{\partial T}{\partial t} = (\vec{v} \cdot \nabla T)\vec{v} + a\Delta T, \\ \text{In solid phase} \\ c\rho\frac{\partial T}{\partial t} = a\Delta T, \end{cases} \qquad (3)$$

where c – heat capacity.

Solving the thermal problem ensured obtaining isotherms that characterize the temperature regime in the welded joint (Fig. 3). When the temperature fields were studied, the boundary between the liquid and solid phases was determined, as well as the temperature regime of the crystallization process, which made it possible to identify the conditions for the formation of the structure of the weld metal and areas of the HAZ.

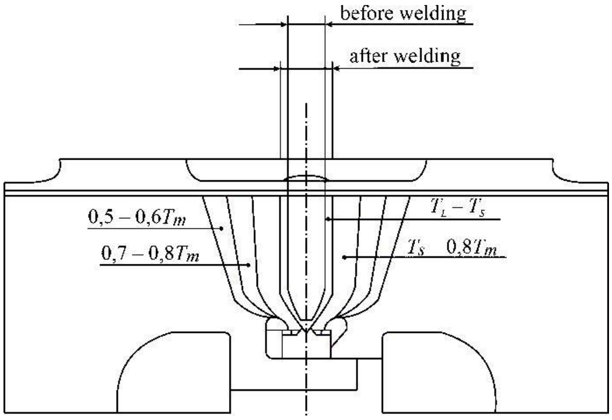

Fig. 3. Fragment of the calculated temperature fields in the pilot sample of the welded connection of the rotor

The numerical solution of the thermal problem (1)–(3) provided obtaining smoothly approximated temperature isotherms along the cross section of the welded joint (see Fig. 3) which allowed:

1. To clarify the peculiarities of structural and phase transformations in the weld metal and in the HAZ areas of welded joints.
2. Identify (for the next warning) places of local overheating of the weld metal and areas of the HAZ, where defective structures or structures that are close to defective ones are formed.
3. To estimate the general level of structural heterogeneity of the metal of the welded joint.

RESEARCH RESULTS

The results of modeling the temperature regime in the welded joint of the witness sample were controlled by practical determination of temperatures at fixed points of the HAZ and weld metal areas, as well as by analyzing the structure. Such control made it possible to choose correction factors, the use of which ensured the refinement of the numerical data of welding heating simulation.

Based on the simulation data, the optimized parameters of the automatic welding mode were recommended: welding current, 370…420 A; arc voltage, 38…40 V; electrode wire feeding speed, 125…130 m/h; welding speed, 20…25 m/h; diameter of the electrode wire, 2.5 mm; running energy, 2.7…3.0 kJ/mm. On the templates that were cut from the witness samples (Figs. 4–7) studied the structure, chemical composition and properties.

Welding of the root of the seam (see Fig. 1) was performed using electrode wire Св-08Г2С (GOST 2246-70), and for welding the main seam, electrode wire Union S3NiMo, type SZ3Ni25CrMo EN14295 was used. To protect the welding zone, we used a UV 420TT flux, type SAFB165 DS in accordance with EN76. Preliminary and accompanying heating during welding was 350 °C.

In order to clarify the assessment of the increase in the resource of the welded joint, short-term mechanical properties, coercive force and density of dislocations were determined (a fine structure analysis was performed), as well as an analysis of the structure at the micro level (optical microscope) (see Figs. 4–7).

It was established that the structure of the weld metal includes ferrite and bainite (see Fig. 4). Bainite has a predominantly grain structure, close to rounded. Along the body of grains of the α-phase (tempered bainite) and along their boundaries there are separations of other phases. The ratio of ferritic and bainite grains met the regulatory requirements. Allocations of the second phases are also located along the matrix ferrite body, but their number was much smaller.

Fig. 4. The structure of the weld metal, ×400

In the area of fusion of HAZ (see Fig. 5) a smooth transition between the structures of the weld metal and the base metal is observed. The structure of the fusion zone is characterized by the presence of a relatively small number of small grains in the dark granular matrix. There are cementite-type discharges in the form of mainly round fine-dispersed inclusions along the body and along the grain boundaries α-phases Structural heterogeneity is insignificant.

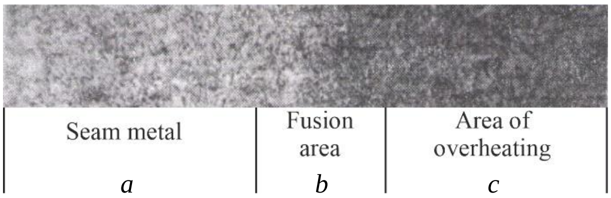

Fig. 5. The structure of the welded joint (see Fig. 1): a – seam metal; b – fusion area; c – area of overheating, ×400

Area of HAZ overheating, fig. 6, had a predominantly sorbitol-troostite structure. Austenite grains in the areas of fusion and overheating corresponded to 6–8 points (DSTU 8972:2019). It was found that the austenite grain score varies with the height of the welded joint. When conducting structural and phase studies, we took into account the previously obtained results aimed at obtaining relatively small austenite grains in the heat-affected zone [3, 5]. However, for the first time, by modeling [1, 2, 4], they solved the problem of obtaining such grains, which significantly increased the properties of welded joints [2, 6]. For example, the area of incomplete recrystallization of HAZ (see Fig. 7), is characterized by the presence of new austenite decomposition products in the form of sorbite.

Fig. 6. The structure of the HAZ overheating section of the welded joint of the experimental sample of the rotor, ×400

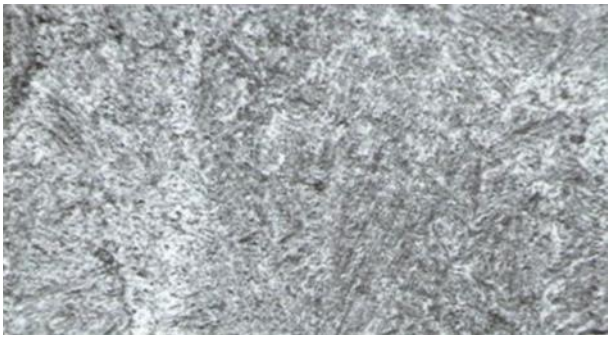

Fig. 7. The structure of the area of incomplete recrystallization of the HAZ of the welded joint of the experimental sample of the rotor, ×400

It was established that the structure of HAZ areas mainly consists of M_3C, M_7C_3, Mo_2C, and VC carbides uniformly located along the body and along the boundaries of α-phase grains.

Measurement of microhardness (see Fig. 8) confirmed the presence in the metal of the welded joint of the experimental sample shown in Figs. 4–7 structures.

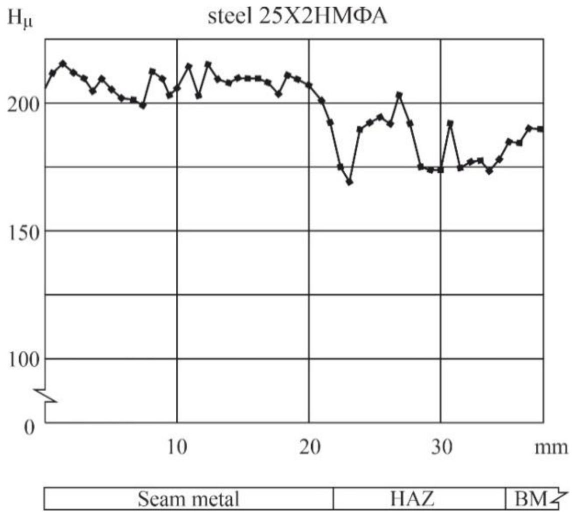

Fig. 8. Distribution of microhardness along the cross-section of the pilot sample of the welded rotor joint

It was established that the mechanical properties of the witness samples (Table 2) as well as the results of the fatigue test, meet the regulatory requirements.

Table 2

Mechanical properties of welded joints

Strength limit, N/mm^2	Yield strength, N/mm^2	Relative elongation, %	Relative narrowing, %	Impact viscosity, J/cm^2	Hardness, HB
780	520	25	63	187	197

It was found that the matrix phase in the areas of fusion and overheating of the HAZ is granular bainite, the formation of which in the process of post-welding cooling takes place according to the martensitic mechanism. The shape of the α-phase grains does not change under tempering conditions. Coagulation of group I carbides is insignificant, and group II is practically absent. The amount of residual austenite (7…9%), which turns into a ferrite-carbide mixture, does not have a noticeable effect on the mechanical properties, which is confirmed by the microhardness indicators (see Fig. 8).

Optimization of welding heating allowed: 1) to reduce the effect of the formation of large austenite grains in the areas of fusion and overheating of HAZ; 2) obtain new austenite decomposition products in the form of sorbite or troostite in the area of incomplete recrystallization and prevent their formation in the form of globularized pearlite. Thus, optimization of welding heating allows obtaining the original structure of welded joints with improved qualitative characteristics of their original structure, which is confirmed by mechanical properties [2, 6]. It should be noted that the mechanical properties of the welded joints of the tested rotor sample are 10…15% higher than those that meet the requirements of regulatory documentation.

The improved technology of automatic welding of high-power turbine rotors made of 25Х2НМФА steel was implemented at the JSC “Ukrainian Energy Machines” enterprise, which ensured a significant economic effect.

CONCLUSIONS

1. It was established that the improvement of the technology of automatic welding of a rotor made of 25Х2НМФА steel, which involved the use of optimized mode parameters obtained by modeling welding heating, ensured the formation of the initial structure of the welded joint with improved quality characteristics.

2. It was substantiated that the prevention of the formation of large austenite grains in the areas of fusion and overheating of the HAZ is provided by the possible way of optimal welding heating of the manufactured joint made of 25Х2НМФА steel.

3. It was established that welding on optimized modes allows obtaining new austenite decomposition products in the form of sorbite and troostite in the area of incomplete recrystallization of HAZ.

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УДОСКОНАЛЕННЯ ТЕХНОЛОГІЇ ЗВАРЮВАННЯ РОТОРА ТУРБІНИ ВЕЛИКОЇ ПОТУЖНОСТІ

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Для вирішення проблеми підвищення надійності і збільшення ресурсу напрацювання зварних з’єднань роторів турбін великої потужності атомних і теплових електростанцій удосконалювали технологію їх виготовлення. Удосконалена технологія забезпечила отримання зварних з’єднань роторів з покращеними характеристиками їх вихідної структури і більш високими механічними і фізичними властивостями. Наведені властивості визначали при порівнянні з аналогічними властивостями, які характерні для зварного з’єднання ротора, виготовленого за штатною технологією. Удосконалення технології передбачало моделювання зварювального нагрівання виготовляємих з’єднань, що дозволило оптимізувати параметри режиму автоматичного зварювання ротора із сталі 25Х2НМФА. Вперше теплову задачу вирішували як спряжену в умовах законів Нав’є-Стокса і Фур’є, що і забезпечило одержання результатів, необхідних для підвищення надійності роботи роторів, а також збільшення їх ресурсу.