IMPROVING THE RELIABILITY OF OPERATION OF WELDED ROTORS IN NUCLEAR POWER PLANT TURBINES

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Ensuring the reliability of operation of welded rotors in relation to increasing their working loads is becoming increasingly relevant. Rotors are one of the most responsible components of nuclear power plants. They are made mainly of 25Х2НМФА steel. The reliability of rotor operation largely depends on the quality characteristics of the initial structure of their welded joints. The introduction of the process of automatic welding of rotors using optimized welding mode parameters made it possible for the first time to obtain an austenitic structure in the areas of fusion, overheating and normalization of the HAZ, the grain score of which is 7−9 (ДСТУ 8972:2019). Also, for the first time, in the area of incomplete recrystallization of the HAZ, new austenite decomposition products in the form of sorbite or trostite were obtained. When welding in standard modes, new austenite decomposition products in the form of pearlite were obtained. The presence of pearlite significantly reduces the resistance of the metal of welded joints to damage under working loads, and sorbite and trostite, respectively, increase this resistance. Optimization of the parameters of automatic welding modes was carried out based on the consideration of the corresponding temperature regime, which was first obtained by modeling the welding heating of manufactured non-separable joints. The modeling involved solving the thermal problem in a three-dimensional formulation. Thus, welded joints of the rotor of steam turbines K-220-44, K-320-23.5, K-540-240 and others were obtained, which are characterized by increased operational properties.

INTRODUCTION

Ensuring the reliability of operation of welded joints of NPP turbine rotors with increasing their working loads is becoming increasingly relevant. The reliability of the metal of welded joints largely depends on the quality characteristics of its structural and phase state and the presence of defects. Welded joints of turbine rotors, for example: K-220-44-2 (NPP "Lovisa", Finland); K-1250-6.9/25; K-325-23.5; K-1000-60/1500; K-1000-60-1500-2, etc. are made of steel 25Х2НМФА Fig. 1.

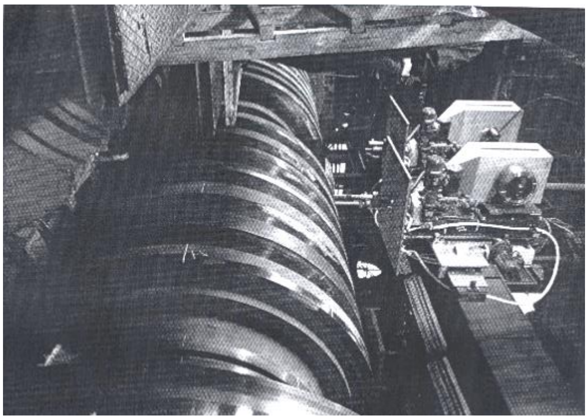

Fig. 1. Technological complex for automatic welding of rotors

When manufacturing welded joints using standard technology, large austenite grains may form in the areas of fusion, overheating and normalization of the heat-affected zone (HAZ) of welded joints, score 3−5 ДСТУ 8972:2019. Chemical compounds and harmful elements phosphorus and hydrogen accumulate at the boundaries of austenite grains, which reduces interatomic bonding forces. Accordingly, the resistance to damage of the metal of welded joints decreases. It is advisable to reduce austenite grains to sizes of 7−10 points. Note that obtaining an austenite structure in the areas of fusion, overheating and normalization of the HAZ of welded joints made of 25Х2НМФА steel is a difficult task. The metal of the above areas is subject to welding heating to the temperature range $Ts-Ac_3$.

It is also important to obtain new austenite decomposition products in the form of sorbite or trostite in the area of incomplete recrystallization of the HAZ. It should be noted that the area of incomplete recrystallization is subject to welding heating to the temperature range limited by the critical points Ac_1-Ac_3. Standard welding technologies allow the formation of new austenite decomposition products in the form of pearlite in this area.

The presence of pearlite contributes to a significant reduction in the resistance of the metal to damage in working conditions. The study of the influence of pearlite on damage has been carried out before [1, 2]. However, an effective method for eliminating its formation and increasing resistance to damage has not been proposed.

It is also necessary to prevent the presence of defects in the initial welded joints: pores, micro-discontinuities, non-metallic inclusions, segregations, non-fusion along the walls of the gap and non-fusion between the rollers in the weld metal. In our opinion, the limiting provisions of the regulatory documentation should take into account the smaller permissible number of initial defects in the metal of welded joints. Such provisions correspond to the increase in working stresses during the operation of rotors.

STATEMENT OF THE PROBLEM

It was taken into account that obtaining fine grains of austenite, as well as sorbite and trostite in the relevant sections of the HAZ is expected to be possible by improving the technology [3−6]. Such improvement involves welding at optimized mode parameters, which were established by modeling the welding heating of the manufactured joints [3−5]. At the same time, to obtain qualitative characteristics of welded joints, it is advisable to improve the modeling of the temperature regime of the manufactured joints.

The solution of the thermal problem allowed us to obtain temperature fields in the manufactured welded joints Figs. 2, 3 according to fixed time indicators, Fig. 4. By using the thermokinetic diagram of steel 25Х2НМФА, we substantiated the temperature regime of welding heating, which ensures the formation of a high-quality initial structure of welded joints. To study the structure and determine the mechanical properties, a special sample of the welded joint of the rotor was manufactured using optimized parameters of the regime, Fig. 2.

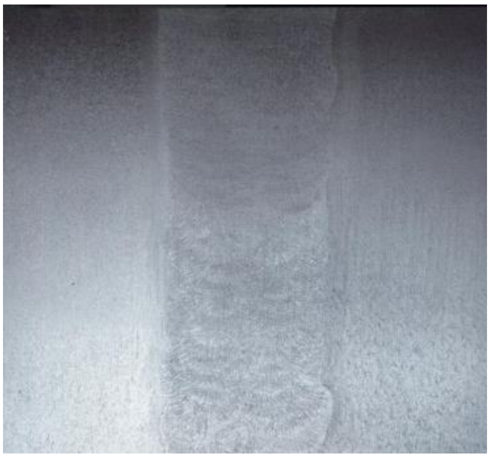

Fig. 2. Macrostructure of a prototype welded rotor joint made of 25Kh2NMFA steel

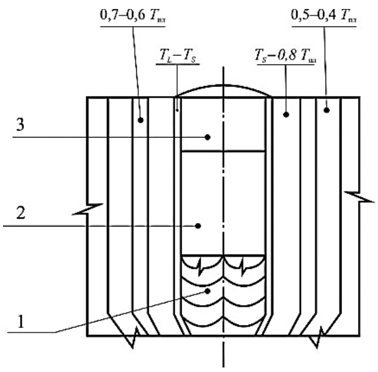

Fig. 3. Scheme of calculated temperature fields in the welded joint of the rotor: 1 – lower zone of the weld; 2 – middle zone; 3 – upper zone

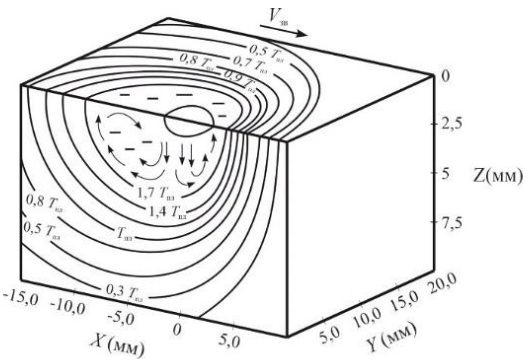

Fig. 4. Fragment of temperature distribution during welding heating of the manufactured joint (see Fig. 2)

The test sample corresponded in chemical composition, structure and heat treatment to the blanks used to manufacture a real welded joint. To compare the structure and properties, a similar sample of the welded joint was also manufactured using standard operating parameters.

RESULTS AND DISCUSSION

The modeling results formed the basis for optimizing the parameters of automatic welding of the experimental sample, the implementation of which ensured: 1. Formation of relatively small, 7–9 point, austenite grains in the areas of fusion, overheating and normalization. 2. Obtaining new austenite decomposition products in the form of sorbite or trostite in the area of incomplete recrystallization (Fig. 5). Reducing the overall structural heterogeneity of the welded joint metal; 3. Preventing the formation of initial defects such as non-fusion along the gap walls and non-fusion between the rollers in the weld metal.

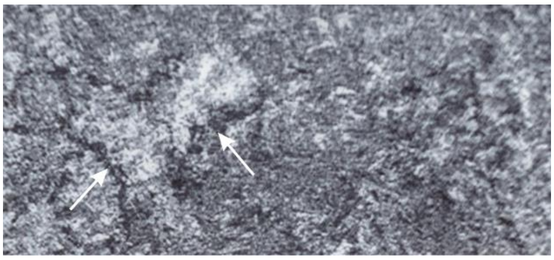

Fig. 5. Structure of the incomplete recrystallization area of the HAZ. New austenite decomposition products located along the austenite grain boundaries (arrows) represent sorbitol, x 400

It has been established that the presence of large austenite grains (score 3−4) significantly contributes to the damageability of the metal of welded joints [1, 2]. Chemical compounds and harmful elements hydrogen, nitrogen, sulfur and phosphorus accumulate along the boundaries of austenite grains. Therefore, reducing the size of austenite grains has become an urgent problem that needs to be solved. Fruitful studies of this problem were conducted by I.A. Borisov [1, 2]. Taking into account the known results of the studies, it was established [3−5] that the solution to the problem of obtaining small austenite grains is possible using modeling of welding heating of manufactured joints. It is the modeling results that allow us to provide, by welding at optimal parameters of the mode, the appropriate conditions for the formation of small austenite grains. According to the modeling results, it was established that zone 3 of the welded joint (see Fig. 3), when compared with other zones, undergoes greater heating in the region of intensive growth of austenite grains, which is limited to Ts−Ac_3. Therefore, when welding zone 3, the automatic welding parameters were correspondingly reduced.

Welding at optimized parameters of the regime allowed to obtain in the area of incomplete recrystallization of the HAZ new products of austenite decomposition in the form of sorbite or trostite (see Fig. 5), and to prevent the formation of pearlite.

It should be noted that the metal of the area of incomplete recrystallization is subject to welding heating in the temperature range limited by the critical points Ac_1−Ac_3. Modeling of welding heating allowed to reduce the time of residence of the metal of this area in the temperature range Ac_1−Ac_3, as well as to ensure the cooling rate for the formation of sorbite or trostite.

It was found that in the samples of each of the 3 zones of the welded joint (see Fig. 3), the size of the austenite grains is close in size and corresponds to 7−9 points. The similar size of the austenite grains in the samples manufactured using standard technology was about 3−5 points.

High tempering of welded joints (600 °C, duration 130 h) allows austenite grains to increase their ability to resist damage. The concentration of chemical compounds and harmful elements accumulated along the boundaries of austenite grains is noticeably reduced, but not completely eliminated. The ability of the metal, in the presence of small austenite grains, to resist damage is significantly greater than in the presence of large ones. It should be noted that damage occurs mainly along the boundaries of austenite grains, which in large grains are correspondingly longer than in small ones.

High tempering ensures that the elongated grain shape in the structure of welded joints is re-deformed into a shape close to round. However, the orientation of the grouped grains in the structure of the weld metal and in the structures of the HAZ sections is preserved (Fig. 6).

Fig. 6. Structure of the weld metal (see Fig. 3), x 400

The mechanical properties of the samples of the 3 zones of the experimental welded joint (see Fig. 3), are 10…15% higher than the normatively established properties (Table).

The process of automatic welding of rotors with optimized mode parameters was implemented at JSC "Ukrainian Power Machines", which made it possible to obtain a significant economic effect.

Mechanical properties of welded joints

Welded joint area	Tensile strength, N/mm²	Yield strength, N/mm²	Relative elongation, %	Relative narrowing, %	Impact strength, J/cm²	Hardness, NV
1	790	530	25	64	186	198
2	770	510	28	67	184	193
3	780	540	24	63	184	197

CONCLUSIONS

1. It was found that the simulation of welding heating, which includes the solution of a three-dimensional thermal problem, allows for more accurate determination of temperature fields in the manufactured welded joint of the rotor.

2. It was found that the simulation of welding heating of manufactured welded joints makes it possible to increase the efficiency of optimizing the welding process modes.

3. It was found that the use of the proposed optimized welding mode parameters in automatic welding of a rotor made of 25Х2НМФА steel allows for obtaining welded joints with high initial quality characteristics. Including obtaining smaller austenitic grains and recrystallized structures in the form of sorbite and trostite in the heat-affected zone of welded joints.

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ПІДВИЩЕННЯ НАДІЙНОСТІ ЕКСПЛУАТАЦІЇ ЗВАРНИХ РОТОРІВ ТУРБІН АЕС

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Забезпечення надійності експлуатації зварних роторів стосовно збільшення їх робочих навантажень набуває зростаючу актуальність. Ротори є одними з найбільш відповідальних складових АЕС. Їх виготовляють переважно зі сталі 25Х2НМФА. Надійність роботи роторів значною мірою залежить від якісних характеристик вихідної структури їх зварних з'єднань. Впровадження процесу автоматичного зварювання роторів із використанням оптимізованих параметрів режиму зварювання дозволило вперше отримати на ділянках сплавлення, перегріву і нормалізації ЗТВ аустенітну структуру, бал зерен якою складає 7−9 (ДСТУ 8972:2019). Також вперше на ділянці неповної перекристалізації ЗТВ отримали нові продукти розпаду аустеніту у вигляді сорбіту або троститу. При зварюванні на штатних режимах отримували нові продукти розпаду аустеніту у вигляді перліту. Наявність перліту значною мірою зменшує опір металу зварних з'єднань пошкоджуваності в умовах дії робочих навантажень, а сорбіту і троститу такий опір відповідно збільшують.
Оптимізацію параметрів режимів автоматичного зварювання виконували на основі урахування відповідного температурного режиму, який вперше отримали шляхом моделювання зварювального нагрівання виготовляємих нероз'ємних з'єднань. Моделювання передбачало вирішення теплової задачі у трьохвимірній постановці. Отже, отримали зварні з'єднання ротора парових турбін К-220-44, К-320-23,5, К-540-240 та інші, які характеризуються підвищеними експлуатаційними властивостями.