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USE OF ELECTRON BEAM WELDING FOR MANUFACTURE OF BLADE PACKAGES FOR COGENERATION STEAM TURBINES

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ABSTRACT

Industrial technology for manufacture of steam turbine blade packages from heat-resistant high-alloy steel of martensitic grade 18Kh11MNFB-Sh was offered. A technological process was introduced into the experimental production, which allowed solving the problem of welding blade packages of 120 mm thickness. The technological equipment was developed, required for positioning package parts in the process of assembly and welding. The results of experimental studies of weldability of heat-resistant steel of martensitic grade by electron beam were presented. It was determined that preheating of blade packages up to 200–250 °C using the defocused electron beam in the vacuum chamber allows obtaining higher ductile properties of welded joints. The required parameters of heat treatment modes after welding were indicated in order to remove inner stresses and provide the necessary mechanical properties of a product.

KEYWORDS: blade package, heat-resistant steel, electron beam welding, heat treatment

INTRODUCTION

Working blades are one of the most critical parts of the steam turbine, which largely determine its reliability and service life. They are subjected to tensile and bending stresses, caused by the action of centrifugal forces, as well as forces that occur as a result of a change in the direction of gas movement in the channels between the blades. In order to increase the vibration reliability of the turbine, its working blades in a quantity from 2 to 5 pieces are joined by welding in packages. It is obvious that the presence of any defects in welded joints located in the tail part of the package creates difficulties during its attachement to the turbine rotor and is unacceptable. This article considers blades of the first stage of the rotor with an all-milled profile, butt welded in a package along the bandage and tail parts. In the world practice of steam turbine construction, for several decades welding of working blades in packages has been used, including electron beam welding [1]. The use of electric arc welding is associated with surfacing of a large volume of metal, which leads to significant residual deformations of steam channels of blade systems. Instead of electric arc welding, which produces relatively massive (volumetric) welds and creates problems of shape deformation of welded products, electron beam welding (EBW) is used, which provides a weld of a better quality without the effect of buckling. A high vacuum in the electron beam chamber contributes to a high metallurgical cleanliness of the welding pool due to its intensive degassing.

In modern steam turbine units operating at high pressures and temperatures of up to 600 °C, in the manufacture of blade packages, high chromium heat-resistant martensitic grades 15Kh11MF-Sh, 18Kh11MNFB-Sh and 20Kh12VNMF-Sh are widely used. Their welding is associated with known difficulties in providing the necessary physical-mechanical and service properties of welded joints. Welding of the mentioned steels is featured by a tendency to delayed failure and softening in the near-weld zone, hot cracking, as well as unstable formation of electron beam welds with a depth of more than 60 mm which is accompanied by the formation of root defects and cavities [2].

In the known works [1, 3], the use of electron beam welding of blade packages was limited to the total thickness of the tail part of 50–60 mm. The design of modern steam turbines requires joining blade packages with the thickness of the tail part of up to 120 mm. Thus, the development of EBW technology for thick-walled structures of heat-resistant high-chromium steel is a relevant and demanded task in industry. The aim of the work was to optimize the technology of welding blade packages of heat-resistant high-chromium steel of martensitic grade 18Kh11MFB-Sh of 120 mm thickness.

MATERIALS AND EQUIPMENT USED IN THE MANUFACTURE OF STEAM TURBINE BLADE PACKAGES

In the work, an example of welding a blade package of heat-resistant high-alloy chromium steel of grade 18Kh11MFB-Sh (EP-291) was considered. It is used

Table 1. Chemical composition of 18Kh11MNFB-Sh steel, wt.%

C	Si	Mn	Ni	S	P	Cr	Mo	Nb	V
0.15–0.21	Not more than 0.6	0.6–1.0	0.5–1.0	Not more than 0.025	Not more than 0.03	10–11.5	0.8–1.1	0.2–0.45	0.2–0.4

for the manufacture of working and nozzle blades of steam turbines at an steam operating temperature of up to 600 °C. The chemical composition of steel is presented in Table 1.

It is known that steel of this grade is hard-to-weld, has a martensitic grade and requires a preheating. In order to provide the necessary service properties, the produced welded joints are subjected to mandatory heat treatment (high tempering).

Preliminary quality testing was carried out with the help of the UDM-3M flaw defector at frequencies of 2.5 and 5.0 MHz. The microstructure was examined with the help of the NEOPHOT-32 metallographic microscope at a magnification of 20–400. Photos of revealed structures were obtained with the help of the digital camera OLYMPUS C-500.

The microstructure was examined on the sections of 23 mm thick. The Vickers's hardness was measured in the M-400 LECO hardness tester at a load of 1 kg.

TECHNOLOGICAL PROCESS OF ELECTRON BEAM WELDING OF A BLADE PACKAGE

Practicing the modes of EBW of heat-resistant high-alloy chromium steel of grade 18Kh11MFB-Sh was carried out on the plates with a thickness of 23 and 120 mm thick, which simulate the welded joint of the bandage and tail parts of the blade package. The works were performed in the laboratory installation of the type UL-209 designed by the PWI with a computer control of all parameters and systems. The installation UL-209 is equipped with the power complex on the base of ELA-60/30 and an electron beam gun that moves inside the vacuum chamber along the linear coordinates *X*, *Y*, *Z*. At an accelerating voltage U_{acc} = 60 kV, electron beam gun with a metal tungsten cathode of 3 mm diameter provides an electron beam current range of I_b = 0–500 мА and the performance of technological beam scanning in the process of EBW (circle, ellipse, stroke) with an amplitude of 0–5 mm. The accuracy of electron beam gun positioning is at least 0.1 mm. The electron beam focusing on the surface of a welded product, its alignment with the butt and visualization of the EBW process while producing technological tacks is carried out by means of the RASTR system in the secondary-emission image. At the same time, the accuracy of alignment of at least 0.1 mm and 5 times magnification of a monitored object are provided.

The quality of the welds was evaluated by the uniformity of facial bead formation and the presence of inner defects in the weld, which was determined by studying macro- and microsections. For blade packages of each type and sizes, the specialized assembly and welding equipment (Figure 1) was developed.

Blade package *7* is mounted in the body of the equipment *1* and fixed in it with the help of embedded tabs *2* and clamping bolts *4*. An accurate positioning of the package in the body of the equipment is carried out by means of the adjustable rest *5* and clamping devices *3*.

The design of the equipment provides the vertical arrangement of the butt plane for both the bandage as well as for the tail parts of the blade package assembled for welding. To fix each body of the equipment on the working Table 1 of the welding installation

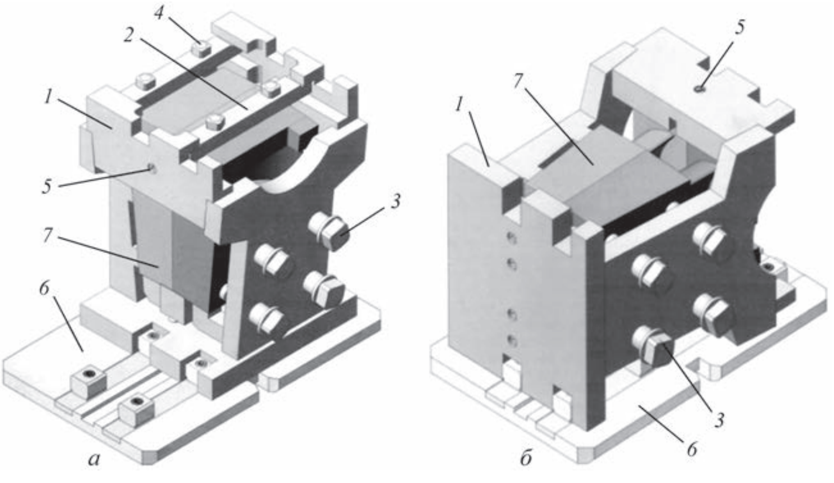

Figure 1. Blade packages as-assembled: *a* — position for welding bandage part of the package; *b* — position for welding tail part of the package

UL-209 in a set position, transitional supporting plate *6* is used.

The process of welding the bandage part of the package runs at the vertical arrangement of the body (Figure 1, *a*). To join the tail part of the blade package, EBW technology with two welds on both sides of this part of the package was offered. Welding was carried out in such a way that the second weld overlapped the first one in the root part by 15–20 % in depth. This technological technique provided joining the parts of 120 mm thick with a relatively small input of thermal energy. And this, in turn, allowed eliminating significant distortion of welded products and minimizing tolerances for their mechanical treatment.

The welding of a thick-walled tail part of the package was performed at the horizontal arrangement of the equipment body (Figure 1, *b*). In order to provide high-quality welded joints when using double-sided welding of the tail part of the package, special attention was paid to producing welds with the rounding in the root and absence of root defects.

To prevent the formation of discontinuities in the metal of the root part, the welds in the cross-section should have the maximum possible radius of rounding the root r_w. The rate of cooling the metal at the weld root at the moment of crystallization is [5]:

$$\left.\frac{dT}{dt}\right|_{T=T_m} \approx -\eta_T \frac{aT_m}{r_w^2},$$

where a is the thermal diffusivity coefficient; η is the thermal efficiency; T is the temperature; T_m is the metal temperature at the time of crystallization; r_w is the root radius.

The higher r_w, the slower the walls of the vapor-gas channel cool down and the molten metal fills the root part of the weld better without the formation of defects in the form of voids and lacks of fusion. To obtain the required radius at the root of the weld, an electron beam scanning in a circle with a diameter of 1.2 mm was used [5, 6]. In a one cycle of pumping-out of the vacuum chamber of the installation, a simultaneous EBW of up to 12 pieces of assembled blade packages (Figure 2) can be performed.

At the first stage, welding along the butt of the bandage part of the package is performed, at the second — of the tail part on both sides is performed. Input and output of welding current is carried out on technological (run-off) tabs that are removed at a further mechanical treatment of the package.

FEATURES OF EBW OF STEAM TURBINE BLADE PACKAGES TABS

The EBW technology with the use of a scanned electron beam for the local preheating of the welded joint zone was proposed. When preheating, the combination of a defocused beam and its oscillation was used.

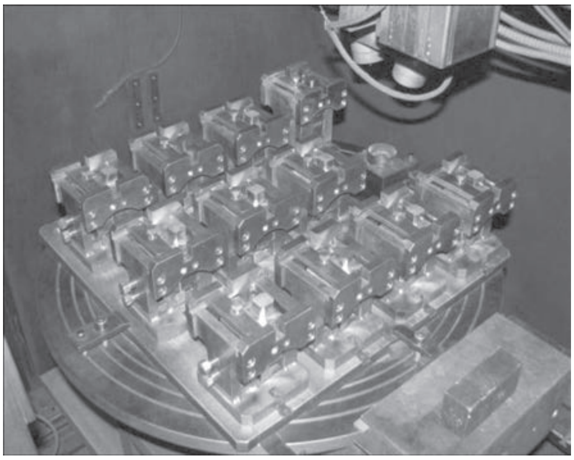

Figure 2. Set of blade packages as-assembled before EBW

It is known that while changing the focusing current, the concentration of the electron beam changes. This can expand its diameter and improve the stability of the channel in the welding pool, which promotes the stability in the formation of welds. It was experimentally determined that in EBW of blade packages of a large thickness, the electron beam focus should locate in the region of a middle penetration depth. This provides the formation of penetrations of up to 70 mm deep without inner defects arising (Figure 3). The location of the beam focus in the lower third of the weld or at the level of the root led to the appearance of root defects.

Welding of the tail part of the package of up to 120 mm thick is performed on two sides by opposed welds. Moreover, each of the welds provides penetration of up to 60 % of the total thickness of the tail part. Here, the size of the overlapping is about 12–18 mm.

The macrosection with the penetration by opposed welds on the specimen with a total thickness of 120 mm is shown in Figure 4.

In order to prevent softening of the welded joint metal at the area of high tempering, the welding speeds should be set within 3–5 mm/s. It is known that the

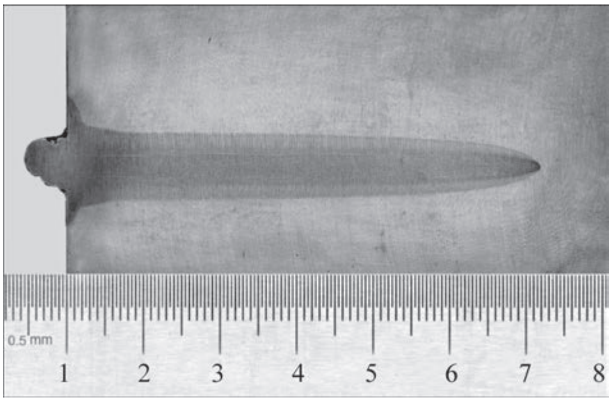

Figure 3. Macrosection of defect-free penetration of 70 mm depth

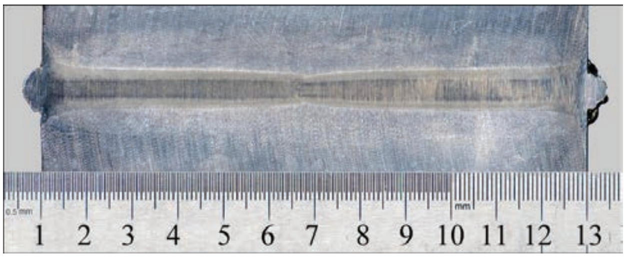

Figure 4. Macrosection with penetration by opposed welds of tail part of the blade package with a thickness of 120 mm

width of the softening zone and the degree of softening increases with an increase in the thickness of the welded metal, since the duration of its stay at a temperature of high tempering at a level of 740–760 °C increases. Therefore, the EBW mode should provide the structure of fine acicular martensite at a thickness of 120 mm, which is favorable in terms of increasing ductility.

In EBW of the tail part of the package with a penetration depth of 70 mm, the optimal frequency of a circular scanning f is 100–300 Hz at a diameter of 1.2 mm. The use of such scanning at a rate of 4 mm/s leads to the formation of the structure of equiaxial crystallites of about 200 μm wide around the weld axis. An increase in the width of the equiaxial crystallites zone to the mentioned sizes prevents the formation of hot cracks and the probability of brittle fracture [7]. Each of the opposed welds was produced at an electron beam current of 320 mA at a welding speed of 4 mm/s.

According to the STP 735.104.-78, in welding of bandage flanges with almost through penetration, the formation of a reverse bead is not admitted. This requirement is performed when the beam focusing at the level of the root part of the butt joint and the electron beam current are at 95 mA for the fixed welding speed of 5 mm/s (Figure 5).

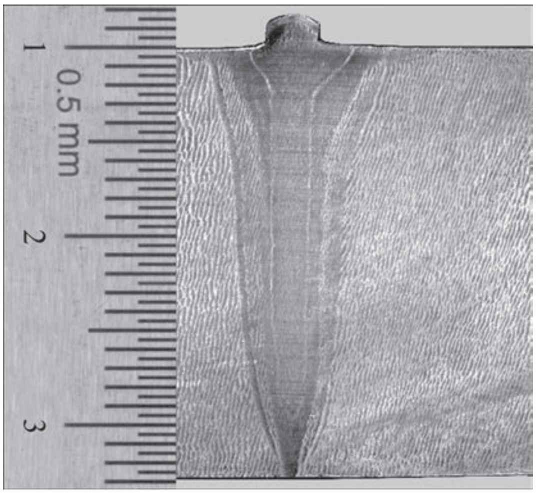

Figure 5. Macrosection of welded joint, produced on the simulator specimen of the bandage part of the package of 23 mm

METALLOGRAPHIC EXAMINATIONS OF WELDED JOINTS OF 18Kh11MNFB-Sh STEEL

The examinations showed that at insufficient preheating (not more than 100–150 °C), in the welded joint metal cracks may form (Figure 6).

Taking into account the need in providing a margin of the technological strength in the development of EBW technology, the temperature of preheating the welded joint zone was determined at a level of 200–250 °C. The preheating temperature was controlled by an optical pyrometer with an error of not more than 1.2 %. The results of the examinations showed that preheating to a higher temperature does not benefit and may cause a reduction in the impact toughness and long-term strength of the welded joint. This can be explained by the fact that in welding of blade packages with a subsequent overlapping of several welds, the introduced preheating $T > 300$ °C reduces the cooling rate in the range of 890–500 °C and shifts the transformation into the bainitic region [8, 9]. The latter is unacceptable since the γ-α transformation occurs with the formation of a coarse-acicular structure of bainite, with low ductile properties of strength. Therefore, the use of preheating temperature higher than $T > 300$ °C is accompanied by softening to 10 % at the zone width of not more than 0.2–0.6 mm, which is associated with crystallite growth and is accompanied by a decrease in a long-term strentgh of the welded joint.

For metallographic examinations, two specimens of the welded joint were used. One specimen was in a state without heat treatment (HT) after welding. The second was after performing HT. The degree of strengthening or softening was determined as a percentage of the values of hardness of the base metal outside the heat-affected zone. The dependence of the weld shape on the EBW parameters was studied on the transverse macrosections cut out from the specimens after welding.

The visual inspection and microscope examination at a slight magnification revealed that the metal of the

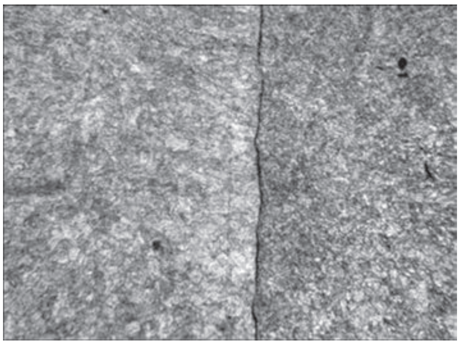

Figure 6. Crack in the welded joint metal produced on 18Kh11MNFB-Sh steel, ×100

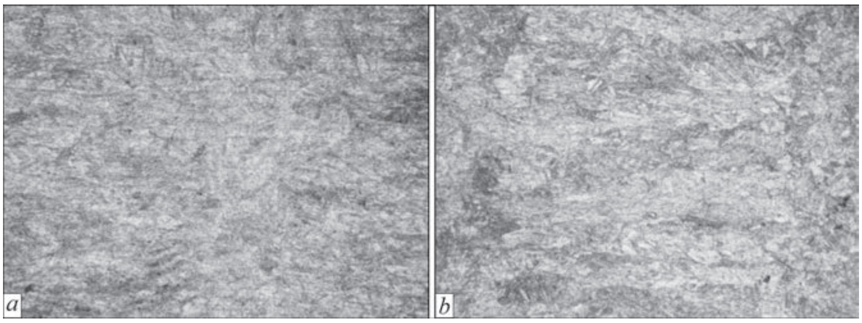

Figure 7. Macrostructure (×200) of a central part of the weld: *a* — without HT; *b* — with HT

specimen weld without heat treatment has a dense structure without visible defects (pores, cracks). The HAZ is symmetric relative to the weld axis. At the root of the weld, the width of HAZ is about 0.5 mm. Further, closer to the upper part of the weld, it gradually grows to 2 mm. Columnar crystallites in the weld grow from the fusion line to the center of the weld at a direct angle to the fusion line, where they collide in the central part of the weld and form a small area of the cellular cast structure of 0.2 mm wide. At the upper part of the weld, the crystallites diverge in a fan shape from the upper edge of the weld. Microstructure of the specimen weld without heat treatment represents a mixture of fine-acicular martensite, a minimum amount of δ-ferrite (about 1–1.5 %), carbides and intermetallics, the composition of which can only be determined by an electron microscope. The maximum hardness was observed on the fusion line and reached 453 *HV*1.

HAZ is represented by a dispersed sorbitic structure with the precipitates of carbides and intermetallics (Figure 7, *a*). Microstructure of the base metal (BM) represents a ferritic matrix with the precipitates of carbides and intermetallics.

The specimen that was subjected to heat treatment after welding has a microstructure of the weld, which is composed of tempered martensite with the hardness *HV*1–343–363 kgf/mm^2, also with a small amount of δ-ferrite (1.0–1.5 %), carbides and intermetallics (Figure 7 , *b*). The HAZ microstructure consists of sorbite, carbides and intermetallics. The BM structure after heat treatment has not undergone significant changes and represents a ferritic base with the precipitates of carbides and intermetallics.

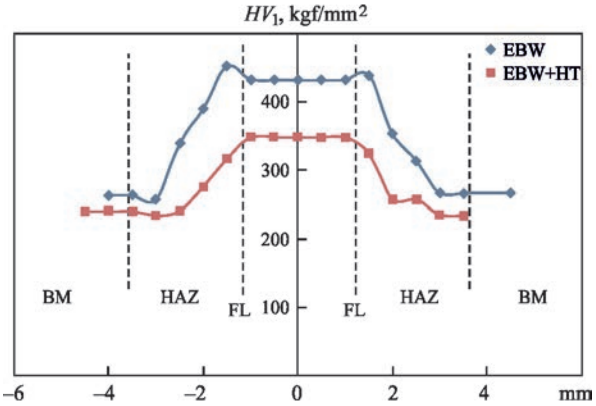

Figure 8. Diagram of hardness distribution in the welded joint of 18Kh11MNFB-Sh steel

Taking into account an increased tendency to brittle fracture of heat-resistant martensitic steels after welding, the blade packages after EBW are subjected to heat treatment to relieve inner stresses and form the structure with the necessary mechanical properties.

The tempering mode for blade packages was as follows: electric furnace temperature during loading - $T \leq 200$ °C. The heating was staged with a holding at a temperature: 1 st. — 200 °C — 2 h; 2 st. — 400 °C — 2 h; 3 st. — 600 °C — 2 h. 30 min. The tempering temperature was 680–700 °C, holding — 4.5 h.

The comparative measurements of hardness of welded joints of 18Kh11MFB-Sh steel in the state af-

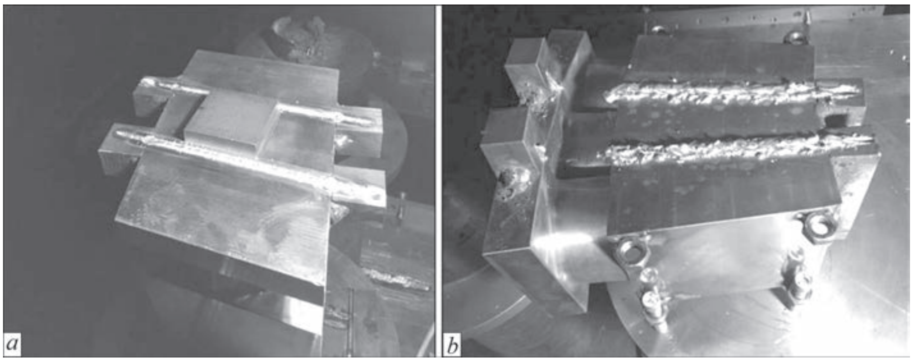

Figure 9. Appearance of the blade package with the tail part thickness of 120 mm, produced with the help of EBW: *a* — appearance of the bandage part of the package; *b* — appearance of the tail part of the package

ter EBW and subsequent high tempering were carried out (Figure 8).

The choice of the optimal heat treatment mode was carried out based on the results of the measurements of hardness of welded joints (in the weld and HAZ metal). After performing high tempering, the difference in the hardness of the weld metal with the base metal did not exceed 20 %, the maximum hardness of the weld metal did not exceed 350 *HV*1. At the same time, softening of the HAZ metal was not observed.

After receiving the optimal modes of both EBW as well as heat treatment, an experimental batch of thick-walled experimental packages of working and lock turbine blades was manufactured (Figure 9).

CONCLUSIONS

1. The optimal thermal cycle in EBW of high-chromium martensitic steel of grade 18Kh11MNFB-Sh is provided during welding with preheating at rates of 3–5 mm/s, which makes it possible to obtain higher ductile properties of welded joints. The preheating temperature of the welded joint zone before EBW at 200–250 °C was determined.

2. The proposed and experimentally proven method of double-sided welding of steam turbine blade packages with a tail part thickness of 120 mm from 18Kh11MNFB-Sh steel allows preventing softening and formation of cold cracks and root defects in the weld zone, practically providing the equal strength of a produced welded joint.

3. The results of optimization EBW technology for thick-walled structures from heat-resistant high-alloy chromium steel allow recommending it for industrial production of modern steam turbine packages. The developed assembly and welding devices and welding technology were used in the manufacture of an experimental and industrial batch of packages of working and lock blades in the amount of 76 pieces at the order of JSC “Poltava Turbomechanical Plant”.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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