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DEVELOPMENT OF BRAZING ALLOY, BRAZING TECHNOLOGIES AND CORRECTION OF CASTING SURFACE DEFECTS OF HEAT-RESISTANT NICKEL ALLOYS FOR SHIP GAS TURBINES

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The aim of the work was to develop brazing alloy and technology of brazing heat-resistant CM93-BI and CM96-BI nickel alloys, used in the production of new generation ship gas turbines. A prerequisite was to provide high-temperature strength of the brazed joints not lower than 80 % of the strength of the base metal. During the development of the brazing alloy, a two-stage procedure was used, where at the first (calculation) stage the required concentrations of alloying elements in the base of brazing alloy, noncompliance of γ- and γ′-phases structure parameters, critical temperatures, number of electron vacancies, physical and mechanical properties of alloys were determined. At the second (experimental) stage, the rational content of the number of depressant elements was determined. As a depressant, boron was chosen. It was established that when using a brazing alloy containing 1.0–1.2 wt.% of boron, the structure of the base metal and the weld are identical. After brazing and heat treatment, boride eutectics in the brazed joints were not revealed. It was established that within the determined limits boron does not reduce the resistance of brazed joints to high-temperature salt corrosion. The surface properties of the brazing alloy and its interaction with CM93-BI and CM96-BI alloys were studied. The developed SBM-4 brazing alloy showed high technological properties and allows raising the temperature of working gas in gas turbines. The developed technology of brazing CM93-BI and CM96-BI alloys provided the tensile strength σ_t at the level of the base metal. The long-term strength of the brazed joints at a temperature of 900 °C was equal to 314–321 MPa on the basis of 100 h, which amounts to 0.89–0.91 of a long-term strength of polycrystalline alloys. The technology of correction of blade defects by SBM-4 brazing alloy was developed. 12 Ref., 4 Figures.

Keywords: brazing alloy, heat-resistant nickel alloys, brazing technology, correction of casting defects, depressant elements, boron, gas turbines, blade

Ship and aircraft gas turbines operate on different fuels, so the chemical composition of heat-resistant alloys for ship and aircraft gas turbines (GT) is different, and the operating temperatures of aircraft turbines reach 1220 °C [1]. Global trends in the development of mechanical engineering indicate a widespread use of welding and related processes for manufacture of structures for different purposes [2]. The main method of joining heat-resistant nickel alloys is brazing [3]. Fusion welding of GT blades does not give positive results because of the hot crack formation of both during welding and heat treatment and leads to softening and destruction of directionally solidified and single-crystal structures [4].

The GT blades of ships are manufactured by precision vacuum casting, each one is produced separately. In the presence of surface defects, it allows correcting them by brazing. With the help of brazing, sign holes of the cooled blades for fixing inner rods are also closed. Taking into account the fact that the essence of brazing consists in reducing the melting point of the brazing alloy by using depressants, an important problem of braz-

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ing is to increase the level of strength of brazed joints to the level close to the strength of the base metal. It is also necessary to provide the resistance of brazed joints against high-temperature salt corrosion (HSC) in the conditions of operation of offshore gas turbines. The most heat-loaded in GT are nozzle and working blades. Taking into account the difficult operating conditions of ship GT, turbines of a new generation were designed, new heat-resistant CM93-BI and CM96-BI nickel alloys (HNA) [5] were developed, which allow raising the operating temperature of the gas by 40–60 °C. To braze new HNA it is necessary to create new brazing alloys with higher melting and brazing temperatures, which provide the formation of joints with a high heat resistance and long-term strength. Solving these problems is very important for the development of ship gas turbine construction. The relevance of the development grows significantly during brazing of new generation materials, which provide higher operating temperatures and service life, in particular, CM93-BI and CM96-BI alloys for ship GT.

Analysis of scientific publications on brazing alloys and brazing technologies of HNA shows that almost all of them are devoted to the development of brazing alloys for HNA of aircraft turbines, for example, ZhS32 [4], ZhS36 [6, 7], ZhS6U [8]. In [8] VPr36 brazing alloy was used, and to reduce the temperature of brazing, NS12 brazing alloy based on the Ni-12Si system was added.

To braze the mentioned alloys, different brazing alloys were used, for example, VPr24, VPr27, VPr36, VPr37, VPr44 (Russia) [9], VN-2, VN-3 (PRC) [10]. VPr36, VPr37 and VPr44 brazing alloys are recommended by the document PO 13-2011 of BIAM for using in the experimental production of aircraft industry for the purpose of brazing heat-resistant alloys, in particular, also on the base of intermetallic Ni_3Al.

In [9], to braze VKNA-4U alloy based on Ni_3Al with EP975 alloy, complexly-alloyed VPr24, VPr27, VPr47, VPr48 and VPr36 brazing alloys were used to join the disc to the blades. The results presented in the work show that all brazing alloys except of VPr36 formed eutectic interlayers, which significantly reduce the strength of brazed joints.

In [10], to braze IS10 alloy at a temperature of 1250–1270 °C as a depressant, brazing alloy with boron was used. In [4, 9] for brazing of ZhS36 and ZhS32 alloys, VPr37 and VPr44 brazing alloys with the brazing temperature higher than 1260 °C were investigated, which are unacceptable for CM93-BI and CM96-BI alloys.

Recently, in [11] brazing alloys were developed, in which as a depressant Zr is used. According to the results of brazing, two brazing alloys with concentrations of 1.0–2.0 wt.% of Zr of the system Ni–Cr–Ti–Nb–Al–(Me)–Zr for brazing of intermetallic alloys at a temperature of about 1250 °C were selected. Brazing alloys using palladium are also being developed, which are still at the stage of studying. In the studied works the procedure of development of brazing alloys is not reflected. Analysis of the literature also showed that no publications on the development of brazing alloys for ship gas turbines were revealed.

The aim of the project is to develop brazing alloy and brazing technology for heat-resistant CM93-BI and CM96-BI nickel alloys for manufacture of new generation ship GT with a high temperature strength of brazed joints not lower than 80 % of the base metal. To achieve this aim it is necessary to solve the following problems:

- to propose a procedure of brazing alloy development using computer programs that determine the distribution of alloying elements in phases, structure stability and strengthening of HNA;
- to choose a rational alloying of the base of brazing alloy and effective depressants;
- to determine the brazing temperature and other important characteristics of brazing alloy;
- to investigate the surface properties of brazing alloy and its interaction with CM93-BI and CM96-BI alloys;
- to determine the structure, chemical composition and properties of brazed joints;
- to develop the technology of brazing of CM93-BI and CM96-BI alloys and correction of surface defects of castings with HNA.

To determine the composition of brazing alloy, it was proposed to use a procedure consisting of two stages [12]. At the first stage, the chemical composition of the base of brazing alloy is determined, taking into account the peculiarities of operating conditions of the blades of ship GT and the achievements of metals science of HNA. At this stage, computer programs are used available at developers and manufacturers of HNA. It was proposed to additionally introduce chemical elements into the brazing alloy base, which are more effective in strengthening it.

Subsequently, applying calculations by means of computer programs, the rational limits of the content of alloying elements in the base of brazing alloy were determined, taking into account their mutual influence on the number and structure of reinforcing phases, distribution of elements by phases, noncompliance of parameters of crystal structure of γ- and γ'-phases, number of electron vacancies, critical temperatures, physical and mechanical properties of alloys. One of the main criteria in choosing rational alloying limits is minimizing the susceptibility of alloys to formation of brittle topologically close-packed (TCP) phases.

As the base of the filler mertal, CM93-BI alloy was selected, which is alloyed by Re in the amount of 2.4–2.8 wt.% and Ta — 3.3–3.6 wt.%, as far as it is known that rhenium efficiently strengthens HNA, and tantalum improves thermal stability of γ′-phase.

According to the results of calculations, an excessive alloying of alloys with the elements, that increase the susceptibility to the formation of TCP phases, in particular, Cr, Mo, W, Re, was established. Since W has the largest number of electron vacancies, then in the base of the brazing alloy its content is reduced to 2.0–3.0 wt.%. In order to increase the resistance of the alloy to a high-temperature corrosion, the concentration of Cr was increased to 14.5 wt.%. Into the alloy up to 6.2 wt.% of Ti was introduced in order to reduce the liquidus and solidus temperatures and form a strengthening γ′-phase. Other elements have the concentrations, close to the initial CM93-BI alloy. The average content of the elements in the base brazing alloy amounts to (wt.%): 13.0 Cr; 7.0 Co; 4.0 Al; 4.5 Ta; 3.75 Re; 2.5 W; 1.5 Mo; 5.45 Ti; 0.25 Hf; 0.575 Zr 0.4 Nb; 0.07 C; Ni is the rest.

Having no alternative, as a depressant, boron was chosen. The amount of boron can be determined only experimentally by melting alloys with different concentrations of boron. The first brazing alloy was melted with a concentration of boron being 0.75 wt.%, but it spread poorly even at a temperature of 1230 °C.

To reduce the number of experimental melts, an alloy of five elements was melted, which was designated as 4D with the following chemical composition: 14 Cr; 9.5 Co; 2.5 Al; 2.4 V, the rest is nickel. 4D alloy was added to the first melt of SBM-4 brazing alloy in the amount of 10, 20 and 30 %, which provided a gradual change in the concentration of boron. With the introduction of 10–30 % of 4D alloy, the concentration of boron increases from 0.915 to 1.245 %.

To reduce the number of experimental studies and build a regression model, the method of experimental planning was also used. The coefficients of the model were checked through Student's criterion (*t*-criterion), necessary to determine the significance of the coefficients of the regression equation. For this purpose, a hypothesis was put forward, that a parameter or statistical characteristic of the equation coefficient is slightly different from zero. At the same time, an alternative hypothesis was put forward that a parameter or statistical characteristic is significantly different from zero. If the main hypothesis is incorrect, then the alternative is taken as the truth.

The adequacy of the mathematical model was verified through F-test, or by Fisher's test. According to Fisher's test, a null hypothesis was put forward, the fulfillment of which determines that the calculated mathematical expectation is equal to the known (experimental) expectation. To calculate the F-test, the dispersions of reproducibility and adequacy are used.

Based on the results of investigations, the concentration of boron in SBM-4 brazing alloy was taken equal to 1.0–1.2 wt.%. Based on the average values of boron concentration and the content of alloying elements of the brazing alloy base, SBM-4 brazing alloy for industrial application was melted. The content of chemical elements in SBM-4 brazing alloy is the following: wt.%: 12.5–14.5 Cr; 6.5–7.5 Co; 3.0–5.0 Al; 3.0–6.0 Ta; 3.0–4.5 Re; 2.0–3.0 W; 1.0–2.0 Mo; 4.7–6.2 Ti; 0.2–0.3 Hf; 0.45–0.7 Zr; 0.3–0.5 Nb; 1.0–1.2 B; 0.04–0.10 C; Ni is the rest.

When using the brazing alloy containing 1.0–1.2 wt.% of boron, the structure of the base metal and the weld is identical. According to the results of experimental studies of the interaction of brazing alloy with the base metal, it was found that at a brazing temperature of 1210–1235 °C, the brazing alloy has satisfactory technological properties.

After brazing and heat treatment, in the joints boride eutectics were not revealed.

Alloying of Ta allows increasing the resistance of alloys to oxidation and high-temperature corrosion. While studying embers, it was found that in addition to the protective oxides NiO, CoO and Cr_2O_3, there is also Ta_2O_3 oxide, which does not interact with sodium sulfate and forms a dense protective film that reduces the rate of high-temperature corrosion.

It is known that CM93-BI and CM96-BI alloys have a high resistance to HSC, so it was important to determine the effect of boron in SBM-4 brazing alloy on resistance to it. For this purpose, CM93-BI and CM96-BI alloys with the concentrations of boron being 1.0, 1.2, 1.5, 2.0 and 2.5 wt.% were melted. The tests were carried out at a temperature of 900 °C during 20 h in a melt of salts of 25 % NaCl + 75 % Na_2SO_4. It was found that at a boron concentration of 1.2 %, the resistance of alloys to HSC did not decrease. After melting of SBM-4 brazing alloy, cylindrical specimens were manufactured and investigations on their resistance to HSC were carried out.

Investigations of the structure and chemical composition of brazed joints were carried out on the specimens that were brazed in the same batch with the specimens for mechanical tests or on the specimens after mechanical tests. For mechanical tests, the specimens were brazed at a temperature of 1210–1215 °C with up to 15 min holding and subsequent cooling to 1070 °C and holding for 60 min.

CM93-BI and CM96-BI alloys are used for manufacture of blades with polycrystalline and directional structures. Since producing of several specimens with a directional structure requires special preparation, in the work polycrystalline specimens were used. The tensile strength σ_t of brazed joints was at the level of the base metal. Long-term strength for the joints of polycrystalline CM93-BI and CM96-BI alloys amounts to 0.91 and 0.89, respectively.

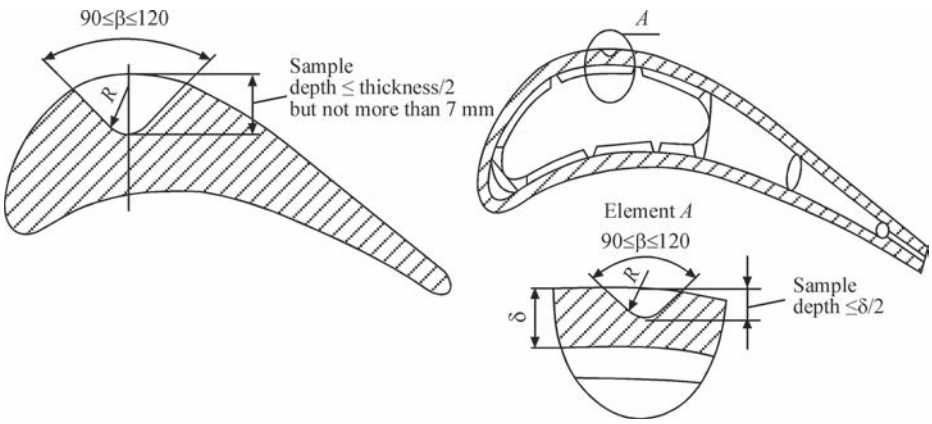

Figure 1. Development of surface defect such as cavity of the blade with a polycrystalline structure of CM93-BI alloy

Defects of the blades can be detected at different stages of their manufacture and operation. The most predictable are defects in castings of the blades. Despite a constant improvement in refractory mixtures for manufacture of ceramic molds, rods, crucibles, filters and casting technology, the yield of suitable blades does not reach 100 %.

Most of the casting defects are superficial. The most widespread are defects in the form of slag inclusions, «beads» and other contaminants of up to 3.0 mm size, have much less discontinuities, underfills and cracks. According to the technological instructions (TI) of NPKG «Zorya»–«Mashproekt», all defects are divided into those, for which corrections are not allowed and surface defects, the correction of which is carried out depending on location area on the blade, sizes of defects and distance between them. On the blades, areas and criteria are marked where correction of defects is allowed. For example, on inlet and outlet edges of the blades correction of defects is not allowed. The surfaces of power protrusions of the blades, radii of the blade feather transitions to the root, etc. are not corrected. Other defects are limited by depth, quantity, size, category of structures. In the course of brazing development, different supplements are introduced into technological documents (2019) and new instructions are agreed.

Depending on the size of a defect, its correction is performed with or without a filler. Small defects (determined according to TI) are corrected by SBM-4 brazing alloy without filler, such defects as cavities are prepared as shown in Figure 1 for blades with polycrystalline structure of CM93-BI alloy.

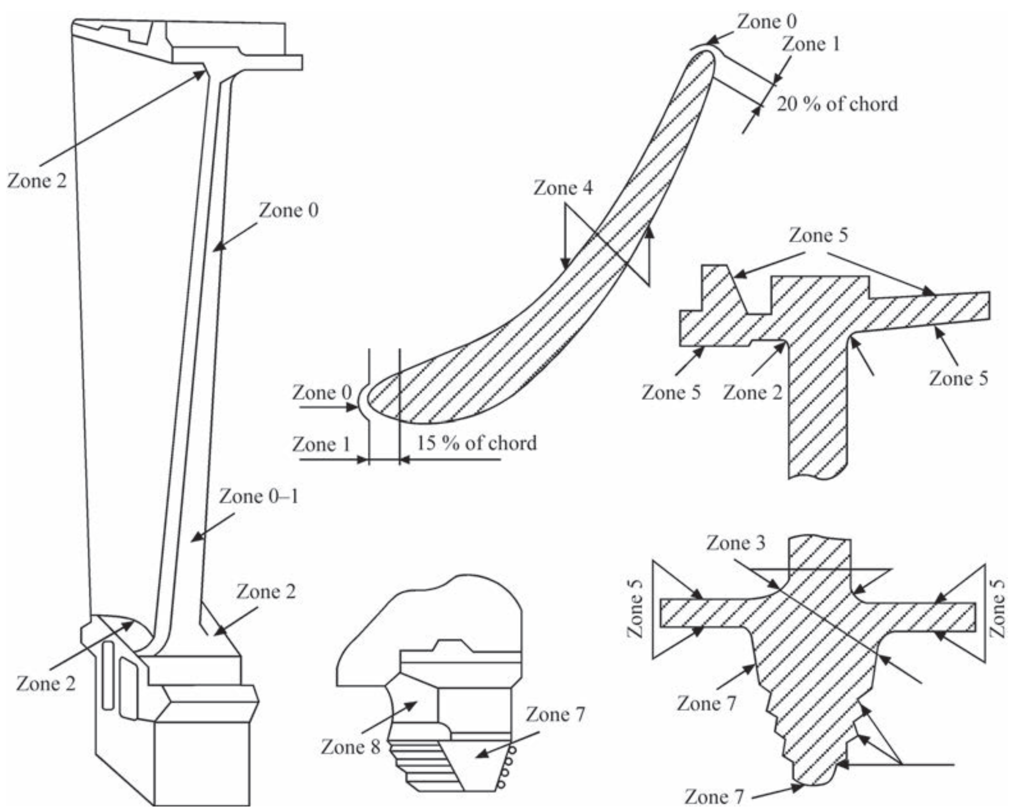

Figure 2. Scheme of working uncooled blade with a single-crystal structure of CM96-BI alloy

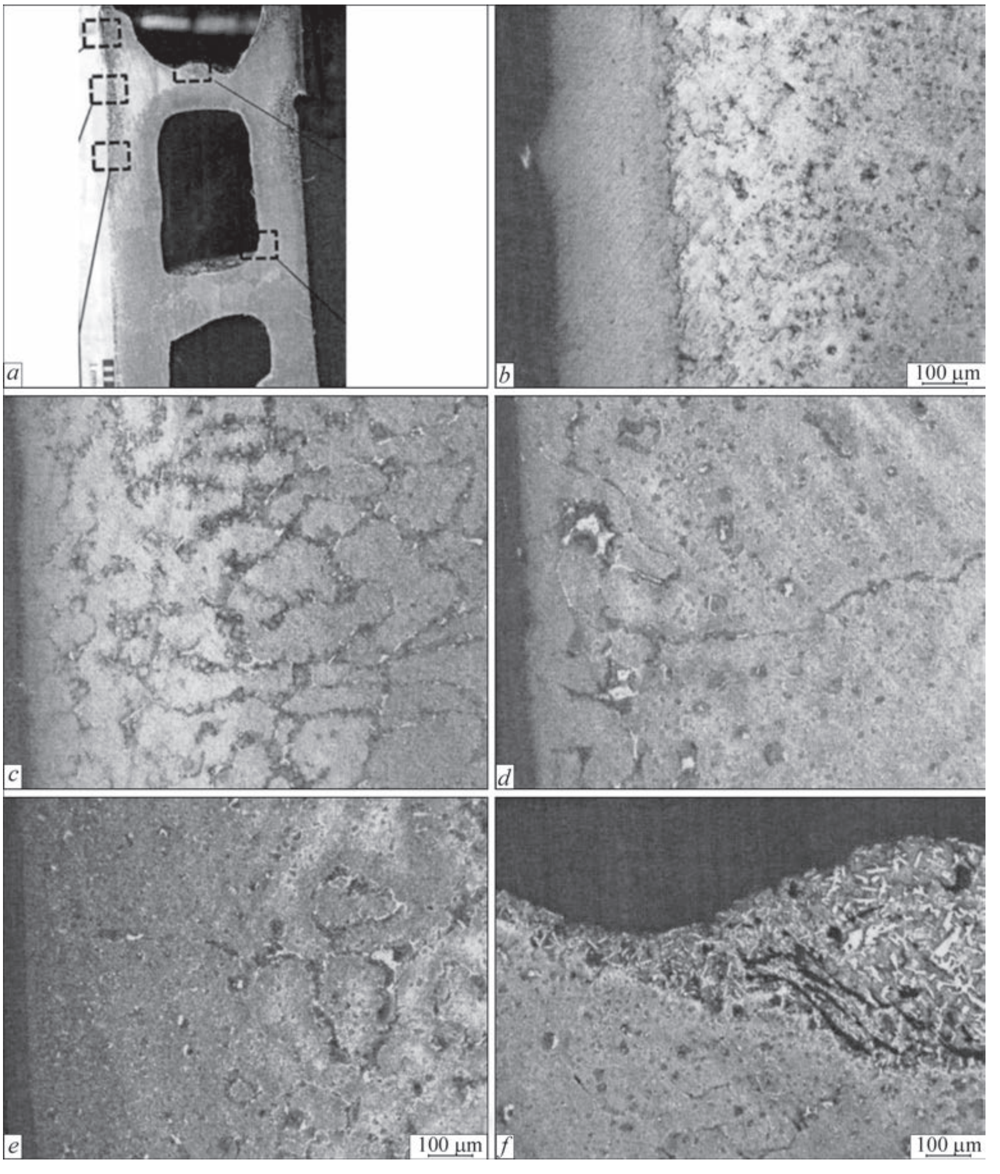

Figure 3. Macrosection of the blade (*a*), microstructure with corrected surface defects (*b*, *c*, *d*), base metal (*e*) and brazed sign hole (*f*)

Correction of casting defects begins at their detection after cleaning and bench work (inspection for defects). Before correction of defects, the blades should undergo the entire step cycle of heat treatment, including homogenization at a temperature of 1180 °C in accordance with the Technological Process. The sizes of defects to be corrected after preparation should meet the requirements of standard documents. The areas to be corrected should be prepared until a complete removal of a defect at an angle of $90° \leq \beta \leq 120°$ in accordance with Figure 1. The surface of the blade around a defect should be cleaned of oxides at a distance of less than 5 mm.

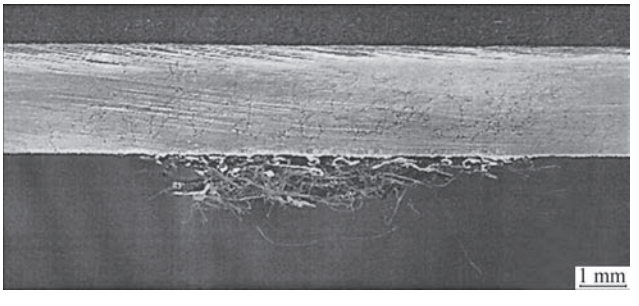

Figure 4. Macrostructure of the blade metal in the area of surface defect correction with a protective coating layer

Figure 2 shows a sketch of a working uncooled blade with a single-crystal structure of CM96-BI alloy and zones of defect location, in which the sizes of defects of GT blades acceptable for correction are regulated by the instructions of the enterprises. The location and sizes of defects on the blades acceptable for correction are regulated by the instructions of the enterprises.

Figure 3 shows the macrosection of the blade of CM93-BI alloy and the microstructure of the metal with corrected surface defects and remelted sign hole. The macrosection in the area of a surface defect correction on the «trough» of the blade with the applied protective coating is shown in Figure 4.

Before applying the correction powder, the surface of the defect should be degreased with alcohol or wiped with a lilac cloth soaked in acetone.

As a filler, the powder of SM88U-BI alloy of centralized production by Ukrspetsstal or high-temperature SBM-3 brazing alloy, developed at NUK and NVKG Zorya-Mashproekt are used. Filler and SBM-4 brazing alloy represent a mixture in a ratio of 1: 1. The powder mixture is fixed on the surface of the blade with a 5 % solution of BMK-5 resin in acetone. The amount of composite powder should be greater than the volume of the prepared defect by 40–50 %. Correction of defects is performed according to the same parameters of the modes as brazing.

SBM-4 brazing alloy fills the gaps well and does not affect the structure of the base metal. Cracks or microcracks during the correction of defects as a result of using brazing alloy are also not observed.

It should be noted that for the current generation of ship turbines for correction of surface defects, VPr11-40N brazing alloy with a melting point of 1020 °C and NS12 with a melting point of about 1150 °C are used, which leads to melting followed by destruction of the protective coating. CM93-BI and CM96-BI alloys allow increasing the brazing temperature to 1230 °C, using SBM-4 brazing alloy, and increasing the life and operating temperature of the gas in the turbine.

Conclusions

1. A two-stage procedure of brazing alloy development was used, according to which at the first (calculation) stage the rational limits of alloying elements in the base of brazing alloy, noncompliance of parameters of γ- and γ′-phases structure, critical temperatures and number of electron vacancies were determined. One of the most important criteria for rational content of alloying elements is to minimize the susceptibility to the formation of TCP-phases, in particular, brittle σ-phase. At the second — experimental stage, rational content of depressant elements is determined.

2. Duirng industrial research tests, SBM-4 brazing alloy showed high technological properties and it allows increasing the temperature of the working gas in the turbine.

3. Brazing and melting temperature of SBM-4 brazing alloy excludes its interaction with the protective coating of the Co–Cr–Al–Y and Y_2O_3 systems during its deposition and heat treatment.

4. For SBM-4 brazing alloy, Temporary technical conditions UKFA 360.107.002-VTU and Technological instruction on correction of surface defects applying the method of brazing in vacuum UKFA 387.341.002-TI were developed.

5. Brazing of polycrystalline blades of CM93-BI alloy is carried out at a temperature of 1200–1215 °C, and from CM96-BI alloy with single-crystal or directionally crystallized structures at a temperature of 1220–1230 °C during 15 ± 5 min. After brazing, the blades are cooled to a temperature of 1070 °C and kept for 60 minutes, then their cooling in vacuum is continued to a temperature of 200 °C.

6. To correct defects, as a filler the powder of CM88U-BI alloy can be used, of centralized production by Ukrspetsstal or high-temperature SBM-3 brazing alloy, developed at NUK and NVKG «Zorya»–«Mashproekt». Filler and SBM-4 brazing alloy represent a mixture in a ratio of 1: 1. The powder mixture is fixed on the surface of the blade with a 5 % solution of BMK-5 resin in acetone. The amount of composite powder should be greater than the volume of the prepared defect by 40–50 %. A defect correction is performed according to the same parameters of the modes as brazing.

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