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DEVELOPMENT OF REMOTELY-CONTROLLED EQUIPMENT AND TECHNOLOGY FOR LASER WELDING REPAIR AND RESTORATION OF PERFORMANCE OF NPP STEAM GENERATORS

V.D. Shelyagin, A.V. Bernadskyi, O.V. Siora, V.A. Kurylo and **O.M. Suchek**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

Control straight butt joints of 10Kh18N10T and 10Kh17N13M3T steel blanks were welded in the vertical position with incomplete penetration by the thickness. Visual and radiographic examination, and metallographic investigations were performed, and welded joint microhardness was determined. Parameters of technological welding modes of the studied circumferential welded joints were established. Conditions of compliance with quality category «high B» of DSTU EN ISO 13919–1:2015 standard were the criterion for selection of appropriate parameters of the modes of laser welding of circumferential butt joints. As a result of work performance, it is shown that the point of welding start influences the dimensions of the weld section, in which the welding process is stabilized, and specified penetration depth is achieved. The techniques developed by the authors were verified on simulator-samples during pilot testing of the model of remotely-controlled equipment developed for repair and restoration of performance of PGV-1000M type steam generators. 18 Ref., 2 Tables, 9 Figures.

Keywords: repair of NPP steam generator, heat-exchanger tubes, laser welding, technology, equipment

Heat exchangers are designed for exchange of thermal energy between two or several environments and they widely applied in power generation, food, chemical and other industries. Combined assemblies from dissimilar metals are quite often used in the structures of heat exchangers to enhance their performance that allows more fully realizing the advantages of each of them. This also raises a difficult issue of fabrication and repair of such structures, as, when it is necessary to apply welding technologies, the problem of welding dissimilar metals has to be solved. Its solution is more complicated, compared to similar material welding [1–3]. An example of the need to perform such welding is installing plugs for sealing heat exchanger tubes in collectors of steam generators of PGV-1000M type for their repair.

In Ukraine 15 nuclear power units are in service in the four operating nuclear power plants (NPP), of which 13 are of WWER-1000 type and two are of WWER-440 type, of the total installed capacity of 13835 MW [4]. Steam generator of horizontal PGV-1000M type (further on referred to as SG) is a component of NPP circulation loop with water-water energy reactor WWER-1000 and it is designed for producing saturated steam as part of NPP power unit [5]. At present 52 horizontal SG operate in Ukraine, the operating time of which is from 10 to 130 thou h [6]. SG body in its middle part is welded to two vertical collectors of the first circuit designed for connection with 11000 heat exchange tubes (HET) bent into U-shaped coils [5]. The tube bundle with spacing and fastening elements takes up about 78 % of the area of the cross-sectional part of steam generator body. HET in bundles are placed in staggered order with steps of 19 mm by height and 23 mm by width between the axes [7], and minimum distance between HET outer walls is equal to 6 mm (Figure 1). The body of steam generator collector is made from 10GN2MFA steel. The internal surface of the collectors is clad by an anticorrosion austenitic deposit (1st layer is ZIO-8; 2nd layer is EA 898/21B), the thickness of each layer is about 3 mm.

The coil ends on SG made before 1990 were inserted into collector holes with further expansion to the entire inserted depth by the explosion technique [7]. The ends of coils in SG manufactured starting from 1990 were expanded after insertion into the collector holes by the method of hydraulic expansion and mechanical final expansion of the outlet section. In both the cases, the coil end faces were argon-arc welded to anticorrosion deposit.

During SG operation different cases of their failure were detected [5–8]. One of the most important con-

V.D. Shelyagin — https://orcid.org/0000-0001-8153-6533, A.V. Bernadskyi — https://orcid.org/0000-0002-8050-5580,
O.V. Siora — https://orcid.org/0000-0003-1927-790X, V.A. Kurylo — https://orcid.org/0000-0003-0790-9404,
O.M. Suchek — https://orcid.org/0000-0002-8961-3887

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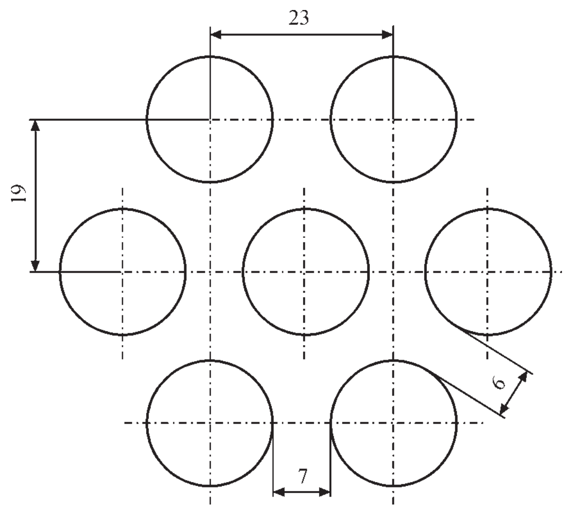

Figure 1. Scheme of heat exchanger tube layout is SG

ditions of safe operation of power units with WWER type reactors is absence of the coolant flowing from the first to the second circuit [8]. Heat exchanger tubes transfer the heat from the coolant of the first circuit to the second one, and act as protection barrier between them. HET damage can lead to penetration of radioactive first circuit coolant into the second circuit that compromises the safety of nuclear power units.

SG HET damage mechanisms are described in detail in the IAEA document [9]. It is shown that the main cause of HET damage is general corrosion, pitting, stress corrosion cracking and a combination of pitting and corrosion cracking. In most cases, degradation starts from point corrosion. After some time, at simultaneous increase of stresses which stretch the tubes in the radial direction, corrosion cracking starts additionally affecting this part of the tube. It is exactly initiation and intensive growth of cracking defects under normal operation conditions that may lead

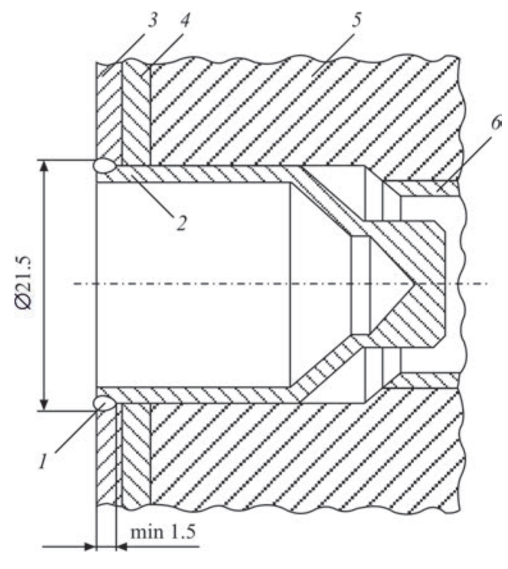

Figure 2. Scheme of plug welding in: *1* — weld; *2* — plug; *3* — first deposited layer; *4* — second deposited layer; *5* — SG wall; *6* — HET

Figure 3. Plug installed using argon-arc welding [18]

to flows from the first into the second circuit. When such a situation arises, the reactor unit is shutdown for unscheduled repair. Defective HET are sealed by placing a plug (Figure 2), which is welded around by argon-arc process. Increase of the number of plugged HET can lead both to considerable financial losses, and to lowering of operating efficiency of the units, because of reduction of heat exchange surface. In keeping with the repair scheme (see Figure 2), the circumferential butt welded joint of the plug with the SG collector body should be made in the vertical position with incomplete penetration (maximum penetration depth of 1.5 mm) and localized fusion zone.

Argon-arc welding [10–12] which is now used at repair, is characterized by higher heat input into the parts being welded and insufficient concentration of the heat source, compared to laser welding [13–17]. Weld form factor K_f (ratio of weld width to penetration depth) is equal to 2–4 in argon-arc welding. If the condition of ensuring minimum penetration depth of not less than 1.5 mm is satisfied, it leads to increase of the diameter of the circumferential welded joint with the plug (Figure 3) [18]. It results in overheating of the parts and negative impact on the adjacent joints, associated with increase of residual stresses. The area of influence approximately coincides with the zone of temper colours (see Figure 3). All this limits the possibilities of application of argon-arc welding for repair of SG of PGV-1000M type.

The urgency of the work consists in the potential for replacement of argon-arc welding technology. The new technology should provide the required penetration depth at reduction of welded joint diameter. It can be achieved at application of local heat sources, such as the laser or electron beam. The authors' idea consists in application of laser welding technology for SG repair. It is exactly the laser beam as a highly-concentrated energy source that can provide an extremely small thermal impact on the structure and longer operating life of welded joints.

Table 1. Chemical composition of welded steels, wt.%

Steel	C	Si	Mn	Ni	S	P	Cr	Ti	Fe
10Kh18N10T	< 0.1	< 0.8	1–2	10–11	< 0.2	< 0.035	17–19	< 0.6	Balance
10Kh17N13M3T	< 0.1	< 0.8	< 2	12–14	< 0.2	< 0.035	16–18	< 0.7	Same

The objective of the work was development of remotely-controlled automatic equipment and verification of laser welding technology for repair and restoration of performance of steam generators of PGV-1000M type.

Materials and experimental procedures. Used as experimental materials (Table 1) were stainless austenitic steels 10Kh18N10T (from which plugs are made) and 10Kh17N13MT (close in its composition to the first deposited layer in SG).

In order to determine the technological features of laser welding of joints of dissimilar stainless austenitic steels in the vertical position, the work was performed by the procedure described below.

1. Control straight butt joints with weld form factor K_f < 1 with incomplete penetration by the thickness were welded in the vertical position on machined 300×100 mm blanks from 3 mm sheets of 10Kh18N10T (ultimate strength σ_t = 520–550 MPa) and 10Kh17N13M3T (ultimate strength σ_t = 510–540 MPa) steels.

2. For each of the produced butt welded joints of dissimilar steels visual and radiographic inspection were performed, and their microhardness was determined.

3. Analysis of investigation results was the base for establishing the parameters of the technological modes of welding the circumferential joints of dissimilar steels.

4. Samples of plate-tube type (Figure 4) were prepared from blanks of 10Kh17N13M3T sheet steel (3 mm thick) of 100×100 mm size with 20 mm hole, which were joined by a circumferential weld to 100 mm long tube billets from 10Kh18N10T steel (with outer tube diameter of 20 mm and 1.5 mm wall thickness) at a horizontal position of the tube. Variation of the technological mode parameters resulted in circumferential butt welded joints with incomplete penetration between the tube and sheet with weld form factor K_f < 1.

5. Each of the produced circumferential welded joints of plate-tube type was tested according to in item 2.

6. Analysis of investigation results allowed determination of the most rational technological parameters of welding the circumferential joints of dissimilar steels for welding in plugs into steam generator heat exchanger tubes.

7. The developed model of a laboratory stand for laser welding in of plugs was used to conduct pilot testing of the created remotely-controlled equipment on simulator-samples.

Work on determination of the technological features of producing circumferential welded joints of stainless steels in the vertical position was performed in the laboratory stand, using Nd: YAG-laser DY044 of ROFIN-SINAR Company, Germany, with radiation wave length of 1.06 μm.

Experimental results. Parameters of technological modes for laser welding of a control straight butt joint of sheet samples, made in the vertical position, were varied in the following ranges: welding speed of 17–100 mm/s; defocusing value of –1–+7 mm; laser radiation power of 1.65–4.4 kW. A lens with 300 mm focal distance and argon as shielding gas with the flow rate of 333 cm^3/s were used in the investigations.

In order to obtain control straight butt joints of sheet samples, quality assessment criteria were used, which meet the requirements of DSTU EN ISO 13919-1:2015 standard «Welding. Electron and laser beam welded joints. Guidance on quality levels for imperfections. Part 1. Steel».

It is found that the characteristic defects which form at laser welding of control straight butt joints of sheet samples from stainless steels in the vertical position can be undercuts, lacks-of-fusion, shrinkage and crater cavities, excess convexity, isolated pores or voids or their sequences.

Results of analysis of the data of metallographic investigations, visual and radiographic inspection of control butt joints of sheet samples were used to select the ranges of parameters of the technological modes of laser welding, which allowed producing butt weld-

Figure 4. Plate-tube type joint after laser welding

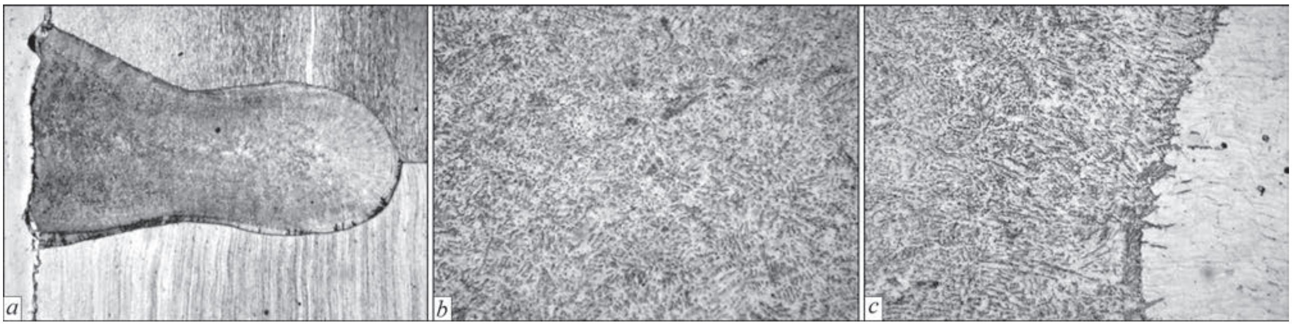

Figure 5. Structure of the produced welded joint of 10Kh18N10T and 10Kh17N13M3T steels: *a* — macrostructure (×50); *b* — metal structure in the weld central part (×400); *c* — metal structure on the fusion line (×400)

ed joints of quality category not lower than «C», acc. to DSTU EN ISO 13919-1:2015.

These modes were used to make in the vertical position the circumferential butt welded joints with weld form factor $K_f < 1$ and incomplete penetration.

During mechanical testing for static uniaxial tension the values of ultimate strength σ_t = 460–475 MPa were obtained at static tension of circumferential butt welded joints of plate-tube type on 10Kh18N10T (tube) and 10Kh17N13M3T (plate) steels. Comparison of the data shows that the breaking force for circumferential butt welded joints of plate-tube type of 10Kh18N10T (tube) and 10Kh17N13M3T (plate) steels is not less than 80 % of the breaking force of the tube base material (10Kh18N10T steel).

Figure 5 shows the photo of a structure characteristic for circumferential butt welded joints of plate-tube type of 10Kh18N10T and 10Kh17N13M3T steels (each 3 mm thick) welded with incomplete penetration in the vertical position with weld form factor $K_f < 1$.

The structure of weld metal of the joint shown in Figure 5, *a* is dispersed cast one, and it is divided into two zones. In the weld central part the structure is cellular-dendritic by the total height. In the weld middle part closer to the fusion line a zone of thin columnar crystallites is observed, which grow in the direction of heat removal. The zones are divided by a line of finer crystallites. The microstructure in the weld central part (Figure 5, *b*) consists of an austenitic matrix with a small amount of δ-ferrite (1.5–1.7 %). The cell size is mostly 12–13 μm. The weld metal hardness in the central part is equal to *HV*1–2950–3090 MPa. In some areas hardness rises up to *HV*1–3200–3380 MPa. In the weld lower part hardness reaches the values of *HV*1–3320–3650 MPa. On the fusion line (Figure 5, *c*) the microstructure also consists of austenite and δ-ferrite, but the structure is finer than that in the weld center. The crystallite width is 2–9 μm. Metal hardness on the fusion line is equal to *HV*1–2990–3030 MPa, with isolated areas, where hardness rises up to *HV*1–3160 MPa. Nitrides (in considerable quantity) are observed in the weld metal. The heat-affected zone (HAZ) is not pronounced, its structure consists of austenite and δ-ferrite. The grain size number in the metal of welded joint HAZ is No.6. HAZ hardness is equal to *HV*1–2650–2840 MPa. Nitrides are found in the HAZ metal.

Discussion. The results of visual and radiographic inspection, metallographic investigations, and static tensile testing were analyzed, in order to determine the influence of laser welding parameters on the characteristics of the produced joints. Graphic dependencies of the characteristics of the produced joints on the most critical factors (technological mode parameters) were obtained.

It was found that at increase of welding speed from 47 mm/s up to 63–72 mm/s, the total projection of pores (total area of pores detected at radiographic inspection) decreases from 0.45 % (of total area of the welded joint) to 0.14 % (Figure 6).

The smallest value of the total quantity of pore projections (0.14 %) was recorded at defocusing of –1 mm that is almost 1.5 times less, compared to welding with similar parameters of speed and laser radiation power, but with defocusing value of +2 mm (Figure 6).

In addition, a greater stability is observed in formation of a small reinforcement (0.7–0.4 mm) of the upper weld bead of the welded joint, at increase of laser welding speed from 47 mm/s to 88 mm/s, respectively (Figure 7).

All kinds of defects of the produced joints were detected. The methods to repair these defects and prevent their occurrence, which were developed and verified by practice, are given in Table 2.

The performed comprehensive analysis of the results of investigations and testing allowed determination of plug welding modes. The criterion for selection of rational parameters of the modes for laser welding of circumferential butt welded joints, were the conditions of compliance with the requirements of «B high» quality category of DSTU EN ISO 13919-1:2015 standard.

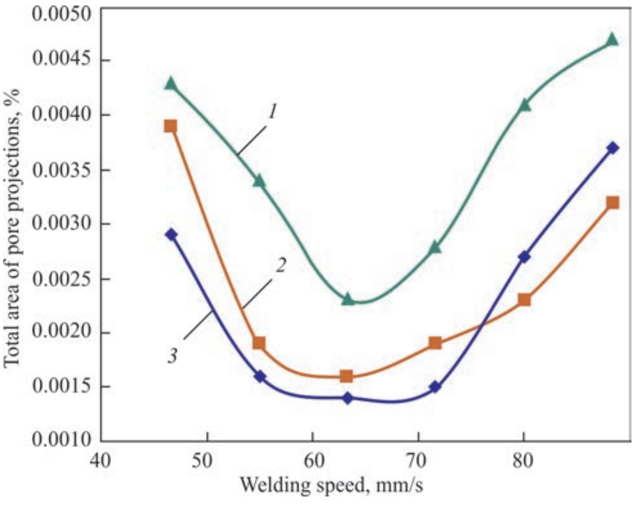

Figure 6. Total area of pore projections depending on speed and defocusing value of laser welding. Defocusing, mm: *1* — +2; *2* — 0; *3* — –1; power P = 4.4 kW

Laser welding of circumferential butt welded joints has the following technological features:

• presence of a section of increase of laser radiation power at the start of welding and section of its decrease at the end, in order to prevent formation of shrinkage and crater cavities;

• parameters of technological modes (laser radiation power; welding time and speed; lens focal position, etc.) for the section of increase of laser radiation power at the welding start and section of its decrease at the end, should be determined empirically for each variant;

• weld sections at the start and end of welding which do not correspond to the conditions of reaching the necessary depth of 1.5 mm, require rewelding, in order to ensure the specified penetration depth;

• unlike arc welding, there is no need for correction of the parameters (laser radiation power: welding time and speed), depending on going through a certain o'clock position, as the process is stabilized after passage of the section with simultaneous increase of laser radiation power and welding speed, and the specified penetration depth can be achieved in all the o'clock welding sections, (downward from 12 to 6 h in clockwise direction, and upward from 6 to 12 h in the clockwise direction, etc.);

• clockwise or counterclockwise direction of movement in welding does not have any significant

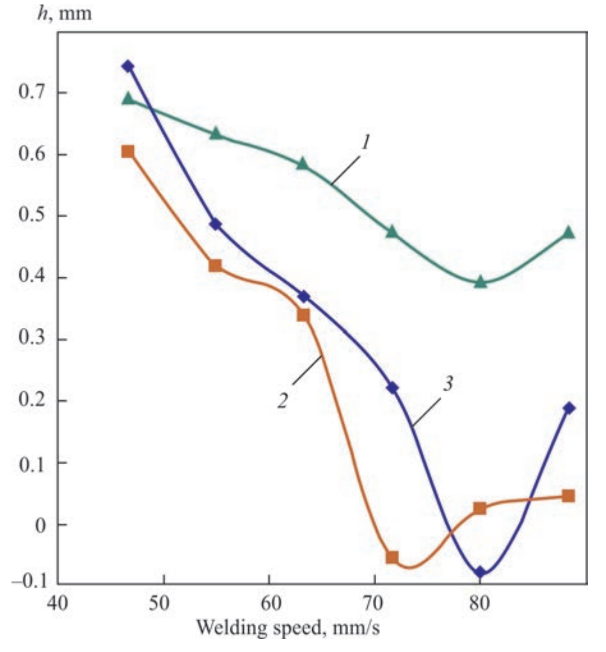

Figure 7. Reinforcement of weld upper bead of welded joint depending on laser welding speed. Power, kW: *1* — 4.4; *2* — 4.0; *3* — 3.6; defocusing — 2 mm

influence on the structure and characteristics of the welded joint, when the specified depth is reached;

• the point of welding start influences the dimensions of the weld section, in which the welding process is stabilized and the specified penetration depth is achieved;

• for welded joints with weld form factor K_f < 1, it is recommended to select 9 o'clock position as the point of welding start and clockwise direction of movement, to achieve quality level «B high».

Welding parameters required to make circumferential butt joints of 10Kh18N10T and 10Kh17N13M3T steels in the vertical position with weld form factor K_f < 1 and incomplete penetration, were determined empirically. They meet the requirements of quality category «B high» of DSTU EN 13919-1:2015 standard.

Conducted comprehensive analysis of investigation and testing results allowed determination of modes for plug welding in. The criterion for selection of rational parameters of the modes of laser welding of circumferential welded joints were the conditions of compliance with the requirements of quality category «B high» of DSTU EN ISO 13919-1:2015

Table 2. Measures for defect repair or prevention

Defects	Repair/prevention
Pores, pore sequences, lacks-of-fusion; weld sinking, lacks-of-penetration	Weld root rewelding with addition of filler material (if required)/–
Shrinkage and crater cavities	–/ program control of smooth increase and decrease of laser beam power at the weld start and finish
Undercuts, excess convexity	–/ additional remelting by a defocused beam
Increase of weld cross-sectional area	–/ widening of the zone of laser beam impact by lens divider

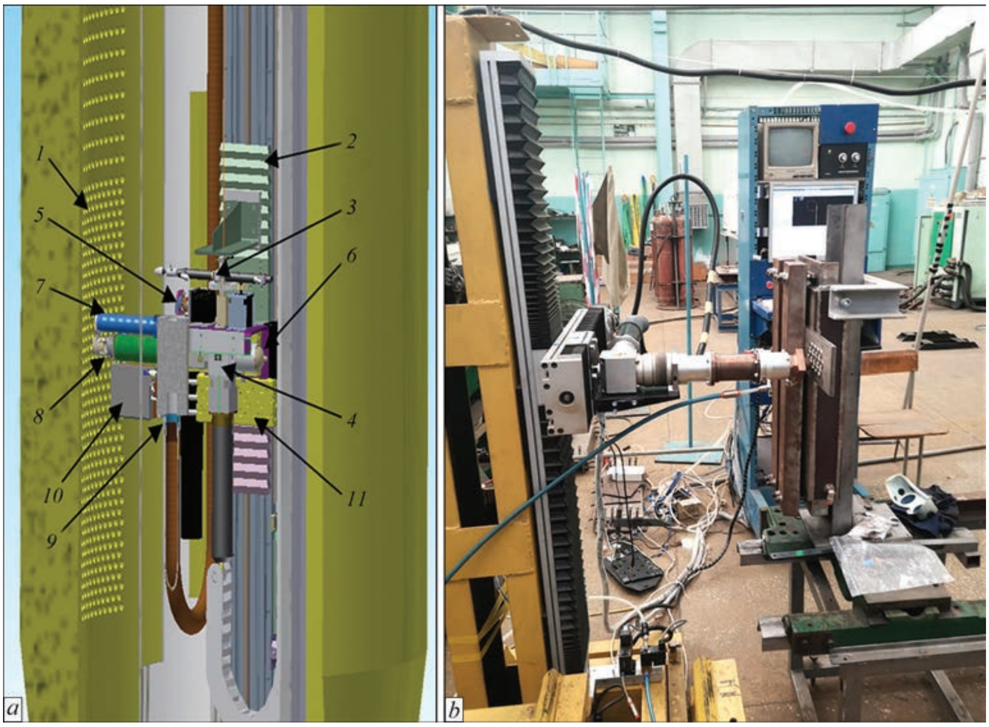

Figure 8. 3D-model (*a*) and working model (*b*) of equipment for remotely-controlled welding in of steam generator collector plugs: *1* — collector wall; *2* — manipulator carriage; *3* — automatic device for installing the plug; *4* — case of laser welding head optics; *5* — scanner; *6* — video camera; *7* — corrugated hose for removing vapours; *8* — gas protection device; *9* — filtering system; *10* — welding position sensor; *11* — drive of welding position sensor

Figure 9. Appearance of welded joints on simulator-samples with plugs welded by laser process

standard. In order to produce welded joints with weld form factor $K_f < 1$, it was proposed to perform laser welding of plugs with the following technological parameters: laser radiation power of 4.4 kW; welding speed of 63.33 mm/s; defocusing value of 1 mm; shielding gas (argon) flow rate of 0.33 l/s (333 cm^3/s); beginning of movement from 9 o'clock position, and clockwise movement direction. During welding in the above mode, the movement mechanism makes two full rotations clockwise, and laser radiation power is varied by a program with a specialized cycle. This way, the stages of increase of penetration depth, its stabilization and decrease are ensured, as well as absence of defects in the form of craters.

A 3D model (Figure 8, *a*) and draft design of the equipment for remotely-controlled welding in of plugs were developed. It was the base for making the working model of a laboratory stand for remotely-controlled laser welding in of plugs (Figure 8, *b*). The created model was used to perform pilot testing of the developed remotely-controlled equipment for repair and restoration of the performance of steam generators of PGV-1000M type on simulator-samples (Figure 9).

Results of visual control and comparative analysis of the geometrical characteristics of welded joints produced by laser (Figure 9) and argon-arc welding revealed the main differences between them. Argon-arc welding is characterized by overlapping of the adjacent welded joints. Unlike argon-arc welding, laser welding provides highly local heat impact that enables extending the service life of welded joints.

Conclusions

1. Remotely-controlled automatic equipment was developed and laser welding technologies were verified for repair and restoration of performance of steam generators or PGV-1000 type.

2. Results of the conducted investigations show that laser welding is a promising technology for replacement of argon-arc welding at repair of steam generator heat exchangers in nuclear and thermal power plants. It provides highly local heat impact and extends the service life of welded joints.

3. Analysis of the main causes for defect initiation at laser welding of circumferential welded joints of dissimilar stainless steels allowed proposing and verifying in practice the measures for repair of these defects and prevention of their formation.

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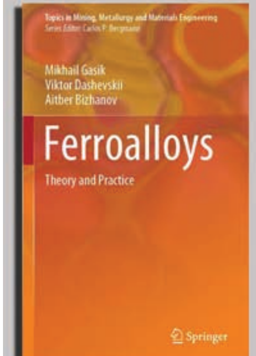
NEW BOOK



Springer Publishing house (Switzerland) has released in 2020 a new book **«Ferroalloys: theory and practice»** (530 p.) by Gasik M.I., Dashevskii V.Ya., Bizhanov A.M., under supervision of Academician of National Academy of Sciences of Ukraine, Professor Mikhail Ivanovich Gasik.

This book outlines the physical and chemical foundations of high-temperature processes for producing ferroalloys with carbo- , silico- and aluminothermal methods, as well as technology practice for manufacturing of ferroalloys with silicon, manganese, chromium, molybdenum, vanadium, titanium, alkaline earth and rare earth metals, niobium, zirconium, aluminum, boron, nickel, cobalt, phosphorus, selenium and tellurium and also iron-carbon alloys. The chapters introduce the industrial production technologies of these groups of ferroalloys, the characteristics of charge materials, and the technological parameters of the melting processes. Special chapters are devoted to description of ferroalloy furnaces and self-baking electrodes in detail. Additionally, topics related to waste treatment, recycling, and solution of environmental issues are considered.

The book is recommended for specialists and researchers involved in the international ferroalloys production.

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