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AUTOMATIC ARC WELDING IN MANUFACTURE AND RENOVATION REPAIR OF PIPE ELEMENTS OF SPIRALS OF HIGH-PRESSURE HEATERS OF NPP POWER UNITS

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The paper considers the possibility for applying automatic orbital welding using nonconsumable electrode in helium or plasma welding using the methods of autopressing or successive penetration to produce welded joints of pipe elements of spirals in high-pressure heaters. The results of testing this technology and the optimal modes of producing position welded joints of pipe elements in spirals of high-pressure heaters of NPP power units are presented. A description of technical proposals on creation of domestic welding equipment for implementation of the proposed technology was presented. It is shown that the use of the developed technology applying domestic equipment can significantly increase the labour efficiency when producing welded joints of pipe elements in spirals of high-pressure heaters and significantly improve their quality. 13 Ref., 3 Figures.

Keywords: high-pressure heaters, spirals of high-pressure heaters, automatic orbital welding, nonconsumable electrode, autopressing or successive penetration, constricted arc, helium arc or plasma welding, position butt joints of pipelines, plasmatron

Pipelines (including high-pressure ones) of NPP power units with WWER light-water reactors, as well as with reactors with boiling water are operated, as a rule, in the conditions of simultaneous exposure to high temperatures, elevated pressure, significant masses of water and/or water steam, as well as penetrated radiation. High-pressure pipelines can also include pipe structures of spirals of high-pressure heaters (HPH), which are important, fundamentally necessary and critical elements of the second circuit of NPP power units. The feed water, entering HPH spirals under pressure, is heated to the required temperature, after which this water enters the heat exchanger — steam generator (SG), where it is converted into steam, supplied to the turbine, which drives electric generators of the NPP power unit [1–3]. The characteristic features of HPH spirals are the presence of welded joints of pipe elements of spirals, as well as the parameters of the medium — feed water, supplied to the spiral at a rated pressure of 12.0 MPa (120 kgf/cm^2), where this water is heated to a temperature of 235 ^{o}C, as a result of which in the course of HPH operation the welded joints of their spirals undergo corrosion-erosion wear. Therefore, designing, manufacture and repair of HPH spirals have their own specifics [3, 4], which determines the technical requirements to the material, design and welded joints of HPH. There are single- and double-plane designs of HPH spirals, but single-plane spirals are the most widespread.

As to its design, the HPH spiral consists of three pipe elements joined by two welded butt joints. The billets for these elements are lengthy sections of a pipe with a rated diameter of 32 mm and a rated wall thickness of 4.0 mm of carbon steel 20. The length of one of the straight sections («central»), which are used as billets for pipe elements of HPH spiral, is 7000 mm, the other two straight sections are 5980 and 5403 mm, respectively, while the «central» section has an area with a S-shaped bend, which, according to the design documentation (DD), is produced before welding, which leads to different spatial positions of longitudinal axes of different areas of this section. All the abovementioned sections on the side of their ends have a V-shaped opening 1-24-1 (C-24-1), which is formed by means of a preliminary machining treatment. After producing welded joints of pipe elements, carrying out their heat treatment and non-destructive testing, from the pipe structure, produced in such a way by means of

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a special device, the spiral structure proper is formed. To the direct inlet and outlet areas of this structure, shanks are welded-on and heat treatment and non-destructive testing of its welded joints are carried out.

Until now, during manufacture and renovation repair of HPH spirals even in the factory conditions in order to produce welded joints of these spirals in domestic practice only manual multipass argon arc welding (TIG) with filler wire feed is used, the main problems of which are insufficient efficiency of these technological processes, impossibility in maintaining stability of quality of welded joints due to its dependence on the «human» factor, need in training and attractment of experienced high-skilled welders. Therefore, providing the growth of welding efficiency and stability of quality of welded joints of HPH spirals during their manufacture and renovation repair at domestic enterprises through the use of automatic or mechanized welding represents an urgent scientific and technical task.

To solve this problem, the possibilities of using various methods of arc welding, including automatic orbital welding using nonconsumable electrode in argon (GTAW), manual and automatic orbital welding using nonconsumable electrode in argon with activating fluxes (ATIG and GTAW-A respectively) and mechanized (automatic) welding using consumable electrode in mixture of shielding gases were previously investigated and analyzed [4]. During these investigations, it was taken into account that according to the Rules and Norms in the nuclear power engineering (PN AE) and other standard documents in Ukraine, welded joints of pipe elements of HPH spirals in the state of straight sections of pipes with a rated diameter of 32 mm and a rated wall thickness of 4.0 m and the opening of the edges being 1-24-1 (C-24-1) of steel 20 should be produced with a complete (100 %) penetration with a maximum reinforcement (2.0 ± 1.0) mm and the convexity of the root weld of not more than 1.5 mm or its concavity, which does not exceed 0.6 mm. The displacement of edges of pipe elements of HPH spirals should not exceed 0.4 mm, and according to PN AE G-7-010−89, welded joints of these pipe elements can be classified as the category III (subcategory IIIc). In accordance with the results of the previous investigations, it was experimentally established that it is fundamentally impossible to achieve the required stable quality of welded joints of HPH spirals and their 100 % penetration by using GTAW process applying the methods of autopressing or successive penetration, developed already in the 1970s and 1980s in the Research and Design Institute of Assembly Technologies (NIKIMT) [5, 6]. Most likely, this is explained by the fact that, firstly, steels of pearlite class (to which steel 20 belongs) as compared to the steels of austenite class are characterized by a much lower coefficient of linear expansion and a significantly higher thermal conductivity, which makes it impossible to provide sufficient compressive forces for the necessary thermoplastic deformations. Secondly, the rated wall thickness of HPH spiral pipeline is 4.0 mm, and the ratio of the wall thickness S to the rated outer diameter of the pipeline D_p is only 0.125, i.e. close to the lower limit of applicability of GTAW applying the methods of autopressing or successive penetration [5, 6]. It was also found that the most effective way to produce welded joints of HPH spirals, as well as other high-pressure pipelines of NPP units, is mechanized multipass arc welding using consumable electrode in shielding gas mixture (it was found that to produce high-quality pipe joints of HPH spirals two welding passes are enough) [4]. However, it should be noted that the proposed technology can be implemented only in the case of using a stationary torch, rotary butts of welded products and innovative technological equipment.

According to the requirements of the effective DD on HPH, welded joints of pipe elements of their spirals are subjected to 100 % non-destructive and selectively destructive testing. Among the non-destructive methods of testing the use of visual-instrumental control (VIC) and radiographic testing (RT) are envisaged [7]. In compliance with the corresponding requirements of the effective production and technical documentation (PTD) and DD on these products, during a selective destructive testing of welded joints of pipe elements of HPH spirals, the check of chemical composition of weld metal and determination of mechanical properties of welded joints as well as metallographic examinations are carried out.

Based on this, in the course of experimental and technological investigations, namely these non-destructive and destructive testing methods were used, and to perform testing by VIC and RT methods, metallographic examinations, mechanical tests and determination of chemical composition of weld metal and heat-affected-zone, the personnel of the department of the chief welder and the metal inspection service SE «Atomenergomash», SE «NNEGC Energoatom» were attracted, as well as the certified standard means available at them.

The analysis of the previously proposed technical solutions and practice have convincingly proved that the implementation of mechanized arc welding of rotary welded joints of HPH spirals using consumable electrode in shielding gas mixture is a rather complex task, which in the vast majority of cases is difficult to perform as far as it requires a complicated and expensive complex of technological equipment for its implementation, where one of the most important basic components is an innovative horizontal rotator [8].

Therefore, at PWI together with the Scientific and Engineering Center of welding and control in the field of nuclear energy additional investigations were conducted to determine the possibility of using constricted arc welding methods for automatic orbital welding of position butts by the methods of autopressing or successive penetration.

The method of helium arc welding is a variety of welding using nonconsumable electrode and it has much in common with argon arc welding using nonconsumable (tungsten) electrode (TIG). The main disadvantage of argon arc TIG and hence GTAW is a free-burning arc, which (especially at low currents) is characterized by a low stability in time and space and a low current density in the anode spot. As the current grows, the diameter of the column of a free burning arc increases, and the concentration of a thermal power on a welded product decreases, which causes an increase in the width of the weld and heat-affected zone (HAZ). In addition, moving away from the tungsten electrode, the temperature of the column of a free burning arc decreases sharply, due to which its ability to penetrate noticeably decreases [9−12]. Therefore, in the case of TIG, and hence GTAW, in order to achieve stability of weld quality, it is necessary to clearly maintain in advance the predetermined values of length of welding arc, which requires the necessary presence of devices and mechanisms or mechanical arc length stabilization systems (ALS) or electronic devices and mechanisms that provide automatic arc voltage regulation (AAVR) in the design of welding heads for GTAW.

The mentioned drawbacks of a free-burning argon arc are excluded during an intense constriction (contraction) of welding arc, which can be achieved in different ways. The most common among them is the use of helium as a shielding gas or a special torch – a plasmatron with a separate supply of plasma-forming and shielding gases and the mandatory presence of a low-power auxiliary («pilot») arc that burns between the electrode and the plasmatron nozzle [11, 12]. The process of welding by constricted arc with the use of plasmatron was called «plasma welding». The column of the constricted plasma arc, which has a temperature of 20000 K and higher, is rigidly stabilized along the axis of the nonconsumable electrode. A high concentration of heat flow of this column on a welded product allows producing welded joints with a deep penetration and a relatively small width of the weld and the HAZ with increasing welding speed, resulting in an increased quality of welded joints. Increasing the guaranteed penetration depth by several times as compared to a free-burning arc allows joining metals of up to 30 mm thickness in a one pass (at the corresponding values of the main arc current and consumption of plasma-forming and shielding gases), and is much higher than that of a free-burning arc, the spatial stability of a constricted arc — to simplify the equipment for automatic welding, because in the case of a constricted arc the need in such devices and mechanisms as ALS or AAVR that support the set values of arc length or voltage constant during the welding process is eliminated [11, 12]. The separate supply of plasma-forming and shielding gases makes it possible to use various mixtures of gases during welding (including those with enriched chemically active gases, which is excluded in the case of a free-burning arc). The use of a low-power auxiliary («pilot») arc provides the stability of welding process in an extremely wide range of welding currents, including their rather small values — up to 0.1 A, which allows welding metals of such small thicknesses that are unattainable with TIG, — up to 0.01 mm thick.

In the vast majority of cases, helium arc and plasma welding is performed by an arc of direct polarity («minus» on the electrode) in continuous or pulsed modes or in a mode of welding current modulation, which burns between the tungsten electrode of the torch for TIG or GTAW or the plasmatron and a welded product (in plasma welding — jets of plasma-forming gas — usually argon). Depending on the physicochemical properties of welded metal, to prevent the interaction of the molten pool of a liquid metal and the near-weld zone with the atmosphere in the case of plasma welding on the periphery of the arc a shielding gas: argon, helium, CO_2, mixtures of argon with hydrogen, argon with helium, argon with nitrogen and other mixtures is supplied [11, 12]. As the current source of the main (welding) arc, an adjustable rectifier of inverter or thyristor type with steeply descending (preferably with «vertical») external volt-ampere characteristics (VACh) and control of the pulse-width modulation method (PWM) is used. As a current source of a low-power auxiliary («pilot») arc, usually a low-power rectifier, which is not regulated or regulated stepwise (also with steeply falling VAChs) is used, which is made in the form of a diode rectifier or converter or of the type AC–DC or DC–DC — power (250−500) V·A.

The sequence of stages of the cycle of automatic orbital helium arc or plasma welding, which is shown in Figure 1, is the following.

When the welding head of the automatic machine for orbital helium arc or plasma welding is mounted on a welded product and fixed on it, the cycle of these welding methods begins after the START signal with the time interval «gas before welding» («pregas») is supplied, during which the supply of shielding gas to the torch for helium-arc welding or supply of plasma-forming and shielding gases to the plasmatron and their free laminar flow from them are provided.

At the end of the specified time interval by means of a special device (exciter) a noncontact ignition of the main arc (in the case of helium arc welding), or auxiliary («pilot») arc (in the case of plasma welding) occurs, which burns between the nonconsumable (tungsten) electrode (with the arising of these arcs, i.e. at the establishment of a stable arc discharge, the exciter automatically switches off), which causes either the excitation of the main arc (in the case of helium arc welding) or blowing of a plasma flame from the

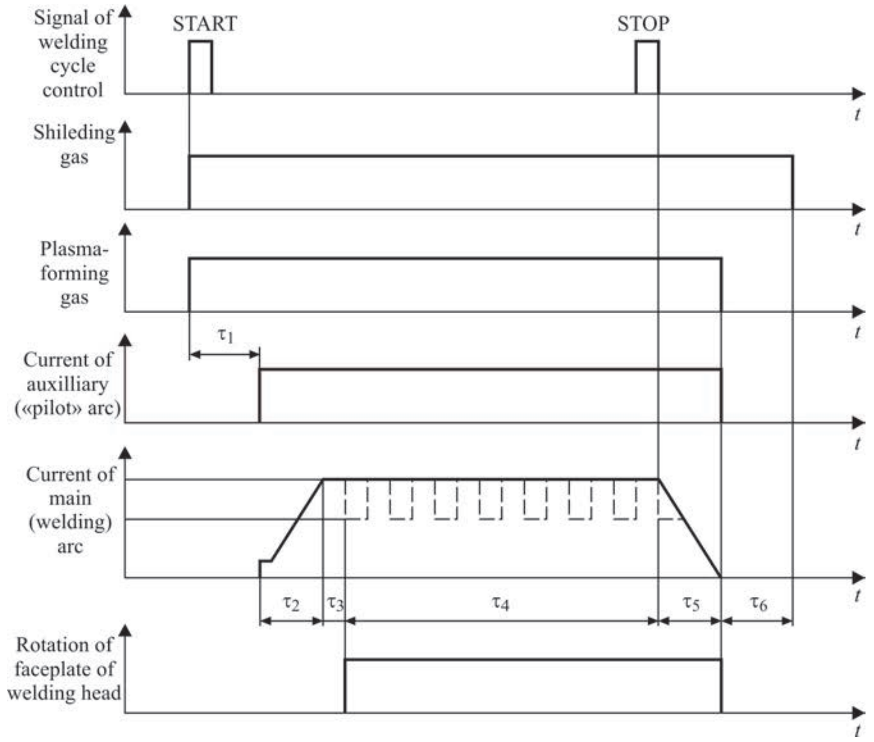

Figure 1. Cyclogram of the process of automatic orbital helium arc or plasma welding of position butts of pipe elements of HPH spirals of NPP power units: t_1 — time interval «gas before welding» («pregas»); t_2 — time interval «smooth increment» of the main (welding) arc current; t_3 — time interval «heating-up»; t_4 — time interval during which welding proper takes place; t_5 — time interval «smooth extinction»; t_6 – time interval «gas after welding» («postgas»)

plasmatron. At the same time, in the installation for plasma welding, the open-circuit voltage in the current source of the main (welding) arc is switched on, which is excited at the lowest value in the range of welding current control when the surface of a welded product is touched with a flame from the plasmatron.

During the time interval «smooth increment» the welding current gradually increases from the smallest value of the control range to its preliminary set (programmed) operating value, which eliminates the electrodynamic impact on the nonconsumable electrode of the torch for helium arc welding or plasmatron («shock» of the electrode).

At the moment of ending the time interval «smooth increment» the time interval «heating-up» begins, during which the formation of a molten pool of liquid metal on a welded product is provided, and the duration of this time interval is much shorter as compared to a free-burning arc. At the moment of ending the time interval «heating-up» on the electric drive of the rotator of the welding head, a signal of permission is automatically supplied and the faceplate of this head with the torch or plasmatron fixed on it begins rotating around the position butt of a high-pressure pipeline with a preliminary set (programmed) and stabilized speed (welding speed), while the welding current either remains unchanged or changes in accordance with a predetermined (programmed) pulsed mode, and in the latter case at the moment of ending the time interval «heating-up» a pause of welding current begins.

From the moment of ending the welding proper the STOP signal is supplied automatically (or manually) and during the time interval «smooth extinguishing» a smooth drop of welding current from operating to practically zero value begins. Thus, if the pulsed mode or the mode with modulation of welding current is provided, then, starting from the moment of reaching the equality of welding current values in a pulse and a pause, welding current will drop synchronously. At the same time both rewelding of a crater, as well as «overlapping» of an initial area of welding are provided, and at the moment of ending the time interval «smooth extinguishing» during plasma welding, the current of an auxiliary («pilot») arc is also automatically switched off, and also rotation of the faceplates of the welding head and the supply of a plasma-forming gas to the plasmatron are stopped. In addition, the time interval «gas after welding» («postgas») begins, during which the welding zone is blown with a shielding gas. At the moment of ending this time interval, the welding cycle is completely finished.

The functional-block diagram of the installation for automatic orbital plasma welding, designed at the Scientific and Engineering Center of welding and control in the field of nuclear energy, is shown in Figure 2. The installation is based on the domestic automatic machines ADTs 625 U3.1 and ADTs 628 UKhL4 for GTAW previously designed at PWI together with the Scientific and Engineering Center of welding and control in the field of nuclear energy. The functional-block diagram of the hardware-software complex for automatic orbital helium arc welding is given in [13] and does not differ from the diagram of the complex for automatic orbital argon-arc welding.

When in PWI together with the Scientific and Engineering Center of welding and control in the field of nuclear energy additional invesitgations were carried out to determine the possibility of using welding position joints of pipe elements of HPH spirals of NPP power units by a constricted arc, the specimens-simulators of pipe elements of HPH spirals of steel 20 with a rated outer diameter of 32.0 mm and a wall thickness of 4.0 mm were used, the ends of which were treated in accordance with the requirements to welded joints of type 1–21–1 (C–21–1) and 1–21–2 (C–39), which are regulated by PN AE G–009–89, PN AE G–010–89 and OST 24.125.02–89.

To conduct investigations on the specimens-simulators of HPH pipe elements of (32×4) mm, a model of an experimental installation was created, which included a modified model of the automatic machine ADTs 625 U3.1 for GTAW, the unit of autonomous cooling of the experimental model of the automatic machine ADTs 628 UKhL4 for GTAW, experimental model of the installation UMPDS–0605 UKhL4 for arc and microplasma welding using nonconsumable electrode and two current sensors — the main and auxiliary («pilot») arc, based on the Hall effect. The power part of the power source (power sources of the main (welding) arc), welding head ADTs 625.03.00.000 (where in the case of plasma welding instead of the standard torch for welding using nonconsumable electrode in inert gases the plasmatron Yu7M3. 045.011-01 with a liquid (water) cooling was installed, control system of the experimental model of the automatic machine ADTs 625 U3.1 for GTAW and the experimental model of the autonomous cooling unit BVA-02 was installed. The basic parameters of the automatic machine ADTs 625 U3.1 for GTAW are given in [13].

The ends of the specimens-simulators of pipe elements of HPH spirals of steel 20, prepared for experimental welding in accordance with the requirements of standard documents, were subjected to automatic orbital helium arc and plasma welding using the methods of autopressing or successive penetration. Previously, applying the TIG method two or three tacks were produced for each weld, for which an experimental model of a specialized power source ITs 617 U3.1 for GTAW or TIG was used. For experimental welding of position butt joints of specimens-simulators of high-pressure pipe elements of (32×4) mm of HPH spirals, the modernized experimental models of the installation UMPDS-0605 UKhL4 and the power source ITs 617 U3.1, as well as the automatic machines ADTs 625 U3.1 and ADTs 626 U3.1 for GTAW, the control systems of these devices and the experimental model of the plasmatron U7M3.045.011-01 were used.

According to the results of several series of experimental welding it was established that:

- butt welded joints of specimens-simulators of high-pressure pipe elements of HPH spirals of NPP power units with WWER type reactors, produced using automatic orbital helium arc or plasma welding, provide the required penetration depth (Figure 3) and have almost no unacceptable defects, spattering and splashes of a welded product, which allows not only a significant (at least 6–8 times) increase in efficiency (as compared to the existing technology), but also a great simplification and reduction in the cost of both preparation for welding as well as for technological equipment to produce the abovementioned welded joints (as compared to the technological equipment for mechanized arc welding using consumable electrode in a mixture of shielding gases). Moreover, a constricted arc welding completely meets the requirements of PN AE G-009−89, PN AE G-010−89 and OST 24.125.02−89;
- the use of automatic orbital helium arc or plasma welding to produce welded joints of pipe elements of HPH spirals of NPP power units with WWER-type reactors is an energy-saving process, because the implementation of the abovementioned welding methods requires welding current (main arc current), which is 1.3−2.0 times lower than during welding using free-burning argon arc;
- to produce high-quality welded joints of HPH spiral pipe elements of NPP power units by means of automatic orbital helium arc or plasma welding using the methods of autopressing or successive penetration, the optimal range of welding modes should have the following values of parameters: in case of welding position butt joints of pipe elements of HPH spirals (32×4), the current of the main arc (welding current) should be in the range from 65 to 80 A, the current of the auxiliary («pilot») arc during plasma welding should be in the range from 3 to 7 A, arc voltage should be in the range from 14 to 16 V during helium arc welding and from 9 to 11 V during plasma welding, the length of the main arc should be in the range from 0.5 to 1.1 mm during helium arc welding and from 3 to 6 mm during plasma welding, the speed of rotation of the faceplate of the welding head should be from 7 to 10 rpm, the number of full-ring passes should be 1−2. The installation (complex) for automatic orbital helium arc welding of joints of HPH spiral pressure elements of NPP power units should at least include the main arc current source (mainly of inverter type) with steeply falling (preferably «vertical») VAChs, a torch mounted on the faceplate of the welding head, modified welding heads ADTs 625.03.00.000 (with the own rotator and controller), welding cycle control unit (WCCU) to control the

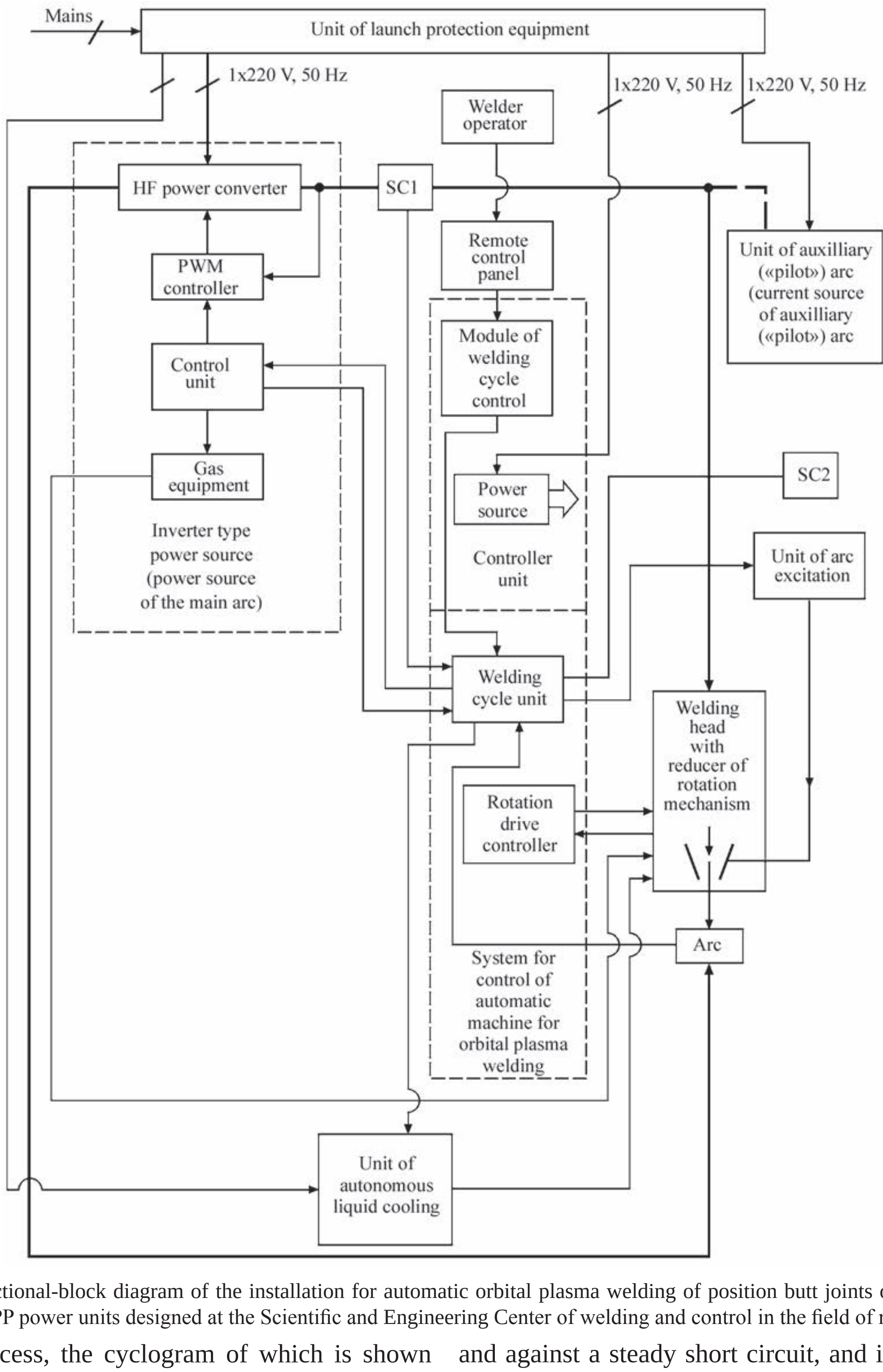

Figure 2. Functional-block diagram of the installation for automatic orbital plasma welding of position butt joints of high-pressure pipelines of NPP power units designed at the Scientific and Engineering Center of welding and control in the field of nuclear energy

welding process, the cyclogram of which is shown in Figure 1, interface unit (controller unit) for communication with all other components of automatic machines for orbital welding and the unit of launch protection equipment (ULPE), which provides the possibility of realizing «EMERGENCY STOP» after the command of the operator or automatically with almost instantaneous and complete deenergization of all without exception components of the hardware-software complex for automatic orbital welding and introduction of their additional protection against a long-term overload on current consumption and against a steady short circuit, and in the case of automatic orbital plasma welding, there is a built-in or separate unit of auxiliary («pilot») arc with steeply falling VAChs and its excitation unit, plasmatron designed for the highest value of the main arc current, autonomous cooling unit of the plasmatron, WCCU, interface unit (controller unit) and ULPE;

● in the process of automatic orbital welding of joints of pipe elements of HPH spirals of NPP power units, stability with accuracy of not worse than ±5 % of such parameters as the main arc current (welding current) at its length of up to 1.5 mm in the case of

Figure 3. Macrostructure of welded joint of specimen-simulator of pipe elements of HPH spiral (position joints), produced using automatic orbital helium arc welding by the method of autopressing, where on the left a weld is shown formed in a one pass by automatic orbital helium arc welding, and on hte right the weld is shown formed by automatic orbital argon arc welding applying the same method

helium arc and from 3 to 8 mm in the case of plasma welding, as well as the speed of rotation of the faceplate of the welding head (welding speed) should be provided; the duration of the stages of which the welding cycle is composed, should be provided with an accuracy of not worse than ±10 %, and the need in the use of preliminary tacks is excluded;

● the duration of the welding cycle during helium arc or plasma welding is (maximum) from 4 to 5 min against (30–32) min according to the existing technology of manual argon arc welding with the filler wire feed.

Conclusions

1. Automatic orbital helium arc or plasma welding of position joints of pipe elements of HPH spirals (32×4) are promising and the most cost-effective methods of welding during the manufacture and renovation repair of these welded structures.

2. The use of automatic orbital helium arc or plasma welding of position butt joints of HPH pipe elements of NPP power units allows not only a significant (at least 6–8 times) increase in welding efficiency (as compared to the existing technology) and a significant improvement in the quality of welded joints of the mentioned pipe elements, which significantly simplifies and reduces the cost for both preparation for welding as well as for technological equipment to produce the abovementioned welded joints (as compared to the technological equipment for mechanized arc welding using consumable electrode in a mixture of shielding gases).

3. The equipment for automatic orbital helium arc welding has a simpler structure as compared to the equipment for automatic orbital plasma welding, therefore, automatic orbital helium arc welding is more preferred.

4. Technical proposals on designing the installations (complexes) for automatic orbital helium arc and plasma welding of position butt joints of pipe elements of HPH spirals of NPP power units were developed.

5. The scope of the basic optimized parameters of the modes of automatic orbital helium arc or plasma welding of the joints of pipe elements of HPH spirals was determined.

6. It is established that the values of the parameters of the modes of automatic orbital helium arc or plasma welding (such as the main arc current (welding current) at its length of up to 2.5 mm in the case of helium arc welding and from 3 to 8 mm in the case of plasma welding, as well as welding speed — the speed of rotation of the welding head faceplate), which correspond to the scopes of the basic optimized parameters of the modes of automatic orbital helium arc or plasma welding of joints of pipe elements of HPH spirals with a rated outer diameter of 32 mm and a rated wall thickness of 4.0 mm using nonconsumable (tungsten) electrode with an accuracy of not less than ±5 %, and the duration of the stages of which the welding cycle is composed, should be provided with an accuracy of not worse than ±10 %.

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