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SELECTION OF WELDING TECHNOLOGY IN MANUFACTURE AND RESTORATION REPAIR OF SPIRALS OF HIGH-PRESSURE HEATERS OF NPP POWER UNITS

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The high-pressure heaters are the fundamentally necessary links of the second circuit of power units of nuclear power plants with light-water WWER-type reactors. They represent single-plane or two-plane pipe spirals of carbon steel. The paper presents the results of selection and mastering the mechanized welding technology for applying in the manufacture and restoration repair of high-pressure heaters. 20 Ref., 2 Figures.

Keywords: *high-pressure heaters, spirals of high-pressure heaters, automatic welding, consumable electrode, electrode wire, mixture of shielding gases, technological equipment, rotary joints of pipelines, welding rotator*

The light-water reactors on heat neutrons (of the PWR and BWR type), in which water is used as a coolant and a moderator, found the widest application in the world nuclear power engineering. The share of power units with such reactors amounts to at least 87 % of the power units of nuclear power plants (NPP) in the world [1, 2].

The high-pressure preheaters (HPH), which are the most important and critical components of the second circuit of pressurized water reactors (PWR), are designed for heating the feed water to the required temperature with its further supply to heat exchanger — steam generator (SG). The steam, produced in SG, enters the turbine, which sets into motion the electric generators of the NPP power unit [1–3].

The PWR-type reactors also include the casing water-cooled (-moderated) power reactors (WWER) operated at all 15 power units of four currently operating NPP in Ukraine. The same reactors are expected to be used in future when creating new power units of the Ukrainian NPP.

The characteristic features of HPH spirals consist in the presence of welded joints of pipe elements of spirals and their tail pieces, as well as in the parameters of the medium (feed water), which is supplied at a nominal pressure of 12.0 MPa into a spiral, where the feed water is heated up to the 235 °C temperature, as a result of which during the operation of HPH the welded joints of their spirals are subjected to corrosion-erosion wear. Therefore, the designing, manufacturing and restoration repair of HPH spirals have their own specifics [3–5], which determines the technical requirements to the material, design and welded joints of HPH.

The appearance of one of the most widespread variants of the HPH spiral is shown in Figure 1.

By the design, the HPH spiral consists of three pipe elements joined together by two butt welds. The semi-products for these elements are the long sections of a pipe of carbon steel 20, having a nominal diameter of 32 mm and a nominal wall thickness of 4.0 mm. The length of one of the straight sections («central»), used as the semi-products for pipe elements of the HPH spiral, amounts to 7000 mm, the

Figure 1. General appearance of HPH spiral

other two straight sections are 5980 and 5403 mm, respectively. All the mentioned sections on the side of their edges have V-shaped groove 1-24-1 (C-24-1), which is formed with the help of previous machining. After producing welded joints of pipe elements, their heat treatment and nondestructive testing, the spiral design itself is formed from the pipe section produced in this way by a special device. To the straight entrance and exit lengths of this structure, the tail pieces are welded-on and a nondestructive testing of their welded joints is performed, which, according to many year experience, HPH are the most susceptible to corrosion-erosion damages during service. Taking this into account, during restoration repair of HPH spirals, the failed tail pieces of steel 20 are replaced by the tail pieces of chrome-nickel steel of austenitic class (mainly of steel 12Kh18N10T).

Until now, during manufacture and repair of HPH spirals, in domestic practice even in the factory conditions, only the method of manual multipass argon-arc welding (TIG) is used for making the welded joints of these spirals, the main disadvantages of which are a low welding efficiency, inability to keep the stability of welded joints quality because of its dependence on the «human» factor, the need to invite the experienced highly qualified welders. Therefore, an increase in efficiency of welding and providing stability of welded joints quality of HPH spirals during their manufacture and restoration repair by using automatic or mechanized arc welding are an urgent task in the domestic enterprises.

For its solution, the capabilities of using different methods of arc welding, including automatic orbital welding by a non-consumable electrode in the inert gas (GTAW), manual and automatic orbital welding by a non-consumable electrode in the inert gas with activating fluxes (ATIG and GTAW-A, respectively) and mechanized (automatic) welding with a consumable electrode in shielding gases, were experimentally tested.

According to the Rules and Norms of Nuclear Engineering and other standard documents, being in force in Ukraine, the welded joints of the pipe elements of HPH spirals should be produced with a full penetration with a force limit of 2.0 ± 1.0 mm and a convexity of the root weld of not more than 1.5 mm or its concavity, not exceeding 0.6 mm. In this case, the edge displacement of pipe elements of HPH spirals should not exceed 0.4 mm, and the welded joints of these pipe elements can be classified as the category III (subcategory IIIc) according to PN AE G-7-010–89.

The welded joints of pipe elements of their spirals are subjected to 100 % nondestructive and selective destructive testing. Among nondestructive methods of testing, the application of visual-instrumental control (VIC) and radiographic control (RGC) is envisaged [6]. At a selective destructive testing of welded joints of HPH spirals of pipe elements, the chemical composition of weld metal is checked and the mechanical properties of welded joints are determined, and the metallographic examinations are also carried out.

While performing experimental and technological works and investigations, the specimens-simulators of pipe elements of HPH spirals of steel 20 with a nominal outer diameter of 32 mm and a nominal wall thickness of 4.0 mm were used, the edges of which were machined in accordance with the requirements of PN AE G-7-009–89, PN AE G-7-010–89 and OST 24.125.02–89.

The E.O. Paton Electric Welding Institute together with the SEC WCNPE carried out investigations on determination of the possibility to use GTAW by methods of auto-pressing or successive penetration, developed at the Research and Design Institute of Site Technologies (RDIST) in 1970–1980 [7, 8]. It was experimentally established [9] that it is not possible to achieve the stable required quality of welded joints of HPH spirals in use of GTAW by methods of auto-pressing or successive penetration because of physical properties of the material of the pipe of HPH spiral and its geometric dimensions. Even at an allowable reduction in the thickness of the pipe wall to 3.6 mm, the penetration of the wall along its entire perimeter was nonuniform in all the cases, and its depth did not exceed 0.8 times of the nominal thickness. This is explained by the fact that, firstly, carbon steels (to which the steel 20 belongs), as compared to the steels of the austenite class, have a much lower coefficient of linear expansion and a substantially higher thermal conductivity, and this does not allow providing the sufficient compressive forces for necessary thermoplastic deformations. Secondly, the nominal wall thickness of the HPH spiral of the pipeline is 4.0 mm, and the ratio of the wall thickness S to the nominal outer diameter of the pipeline D_p is only 0.125, i.e. close to the lower limit of GTAW applying by the methods of auto-pressing or successive penetration. It was experimentally established, that in case of GTAW method application the totality of these factors in combination with real conditions of heat removal does not allow providing neither complete penetration of welded joints of HPH spirals regulated by normative and design documentation, nor the stability of quality of formation of their welded joints.

It is known [10–14] that in TIG or GTAW methods of welding it is possible to increase the penetration depth by 2–3 times by using activating fluxes. However, the disadvantages peculiar to the welding methods ATIG and GTAW-A, connected with the lack of means for mechanized application of activating flux layer, difficulty in control of uniformity of the deposited layer, and also with the possible use of fluxes in the form of aerosols, are the reason of the fact that until now, ATIG and GTAW-A in the domestic nuclear engineering are almost not used.

One of the most widespread and demanded technological processes at different types of production is the mechanized consumable electrode welding in the active gases (MAG), mainly in CO_2 [15, 16].

It is known that as compared to the manual methods of arc welding by coated or nonconsumable electrodes, the MAG process has significant advantages, but at the same time this method of welding has a number of drawbacks, among which the greatest negative influence for welded joints of pipe elements of HPH spirals has a relatively low quality of the weld surface, i.e. the irregularity and coarse rippleness and a relatively low stability of welding process at a significant number of arc gap short-circuits.

As a result of experiments carried out at the SEC WCNPE, it was established that during welding of rotary joints of HPH spirals, the MAG method provides a high efficiency of welding process and the required penetration depth, however, the proper weld formation can not be achieved in principle, and therefore there are all grounds to assume that to produce welded joints of HPH spirals, the MAG process is almost not profitable in practice.

At the same time, in all industrialized countries and in Ukraine, the mechanized welding in mixtures of argon-based shielding gases [17–19] found the wide spreading, in which where a small amount of oxygen or other oxidizing gas (most often CO_2) is added to argon, amounting to 80–95 % of the total volume of the mixture, which significantly improves the stability of arc burning, greatly improves the quality of welds formation and almost excludes the region of welding modes with arc gap short-circuits. In this case, there are regions of welding modes, characterized by either drop or spray (fine-drop) transfer of the electrode metal. As compared to MAG, such nature of mass transfer provides a number of technological advantages. And although in this case, as compared to MAG, the penetration capacity of the arc is by 10–20 % reduced and to obtain the same penetration depth it is necessary to increase the welding current, during welding with consumable electrode in the mixtures of shielding gases, a more quality weld formation is provided (smooth surface with a smooth transition to the base metal); reduction of losses of electrode metal for spattering by not less than 3–4 times; decrease in the labor consumption for cleaning of base metal from spatters by not less than 8–10 times; creation of favorable conditions for use of pulsed processes [18, 19]; the possibility of welding at direct current of straight polarity and with extended stickout; higher mechanical properties of weld metal.

Taking into account the advantages, typical to the method of welding with a consumable electrode in mixtures of shielding gases, as well as the results of the search and experimental-technological works, carried out by the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine and the SEC WCNPE, it should be noted that automatic arc welding with consumable electrode in mixtures of shielding gases is one of the most efficient and promising ways for producing welded joints of pipe elements of HPH spirals. At the same time the most rational is the use of rotary joints.

To carry out experimental and technological works for making the rotary welded joints of pipe HPH elements using MAG and welding with a consumable electrode in the mixtures of shielding gases, the mock-up of the welding installation was created at the SEC WCNPE, which includes a welding rectifier VS-300B, semi-automatic machine A-547 with experimental models of control panel and torch, designed for feeding the electrode wire with a nominal diameter of 1.0–1.2 mm, as well as a rotator mock-up. The main parameters of the rotator mock-up are given below.

Basic parameters of the rotator mock-up

Nominal diameter of pipe elements of HPH spirals, mm	32
Nominal wall thickness of pipe elements of HPH spirals, mm	4.0
Limits of rotation speed control (welding speed) of workpiece welded, rpm, not less than	1.0–7.0
Rated voltage of single-phase supply mains of 50 Hz frequency, V	220
Power of supply unit (converter AC–DC) of rotator reversible electric drive, W, not less than	200
Nominal output voltage of the direct current of rotator reversible electric drive, V	24

The specimens-simulators of pipe elements of HPH spirals of steel 20 with V-shaped groove, prepared for welding according to the requirements of normative documents and the Design Documentation, were subjected to mechanized welding: MAG and consumable electrode welding in the mixtures of shielding gases. Preliminary, TIG method was applied to make two or three tack welds for each joint in an argon at welding current of 80–100 A, for which an experimental sample of a specialized power source ITs 617 UZ.1 for TIG was used. According to the results of several series of experimental welding, it was established:

• welded joints, which were produced by MAG method with forced short-circuits of a thin electrode wire, provided the necessary penetration depth, but required a careful selection of welding mode and maintenance of parameters of this mode during welding process with an accuracy of not worse than ± 5 %, moreover, in some specimens-simulators of the pipe elements of HPH spirals, the welds defects were observed, the most characteristic of which are weld sagging, undercuts, absence of a smooth transition to the base metal, coarse rippleness of finishing surface;

• welded joints, which were produced by consumable electrode welding in shielding gas mixtures, not only provided the necessary penetration depth, but also almost did not have inadmissible defects, moreover, in this case a favorable transfer of electrode metal was observed, in which there was almost no spattering of a workpiece welded, and the quality of welded joints fully meets the requirements of PNAE G-7-009–89.

Also, the main requirements to the technological equipment for mechanized welding of joints of pipe elements of HPH spirals (by method of consumable electrode welding in the shielding gas mixtures) were determined and optimized. The values of the main optimized parameters of the technological equipment for mechanized welding with consumable electrode in mixture of shielding gases of joints of pipe elements of HPH spirals are given below.

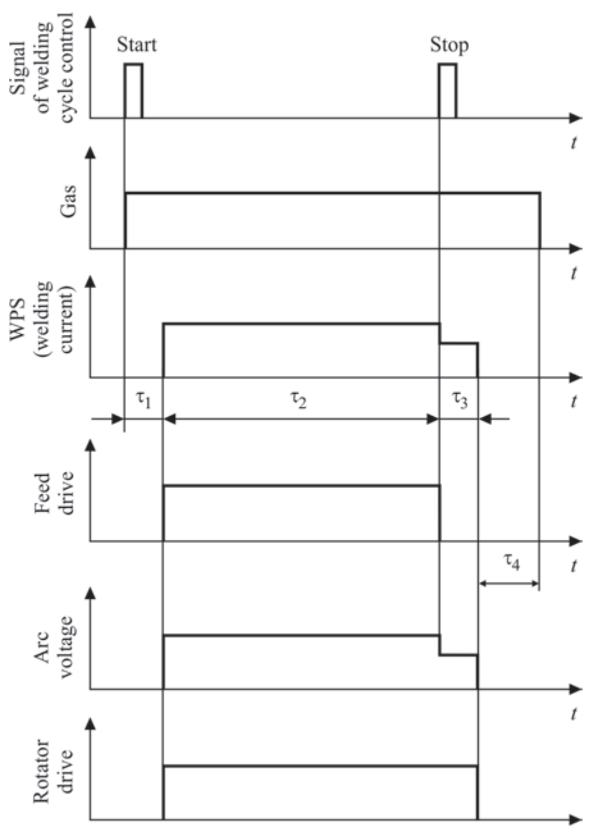

Figure 2. Cyclogram of the welding process of pipe elements of HPH spirals: τ_1 — time interval «gas before welding»; τ_2 — time interval during which the welding proper takes place without a break between the first and second passes of the arc ; τ_3 — time interval during which «stretching» of welding arc occurs until the moment of its complete break and the «crater' rewelding ; τ_4 — time interval «gas after welding»

The main optimized parameters of technological equipment for mechanized welding of joints of pipe elements of HPH spirals by a consumable electrode in a mixture of shielding gases

Nominal diameter of pipe elements of HPH spirals, mm	32
Nominal wall thickness of pipe elements of HPH spirals, mm	4.0
Range of welding current control, A	110–130
Range of operating arc voltage control, V	20–24
Nominal diameter of consumable electrode (electrode wire) predominantly of grade Sv-08GS or Sv-08G2S), mm	1.0
Range of control of rotation speed of workpiece welded (welding speed), rpm	1–7
Range of control of feed speed of consumable electrode (electrode wire predominantly of grade Sv-08GS or Sv-08G2S), m/h	120–160
Displacement of axis of consumable electrode (electrode wire) relative to the vertical («zenith»), angular deg	15–20
Displacement of axis of consumable electrode (electrode wire) relative to the vertical («zenith»), mm	10–15
Number of full-circumferential passes of arc while producing one welded joint, not more than	2
Duration of cycle of one joint welding, s, not more than	5.0
Torch cooling	Gas

It was established in the course of experimental and technological investigations, that in addition to meeting the requirements, the technological equipment for mechanized welding of pipe elements of HPH spirals should provide the stability of welding parameters such as welding current, operating voltage of welding arc, speed of rotation (welding) at an accuracy of not worse than ± 4 %, the speed of consumable electrode (electrode wire) feed at an accuracy of not worse than ± 5 %, duration of welding cycle at an accuracy of not worse than ± 10 %, and also a reliable clamping and aligning of both pipe elements to be welded together in order to perform their synchronous rotation and exclude the need in applying preliminary tacks.

Proceeding from this, the innovative technical proposals on construction of the main parts of such technological equipment were developed by the SEC WCNPE. One of the most important basic components of the complex of technological equipment for mechanized welding of pipe elements of HPH spirals is its horizontal rotator.

According to the technical proposals developed at the E.O. Paton Electric Welding Institute together with the SEC WCNPE, the welding part of the complex of technological equipment for mechanized welding of pipe elements of HPH spirals should at least contain a welding cycle control unit (WCCU), welding power source (WPS), mainly of an inverter type, with rigid or flat falling external volt-ampere characteristics (VAC), MIG/MAG torch with gas cooling and a unit of start-protective equipment (USPE).

WCCU is intended for controlling the welding process, the cyclogram of which is shown in Figure 2. WCCU provides two ways for control of the work of the components and executive mechanisms of technological equipment for mechanized welding of pipe elements of HPH spirals — «manual» and «automatic» at two types of operation of this equipment — «setting up» and «welding», as well as smooth regulation and preliminary presetting the values of electrode wire feed rate, duration of the gas before welding time intervals, of the welding process itself (before the moment of coming the leading edge of the signal (pulse) «stop», «gas after welding» and automatic stabilization of these values during the process of setting up or welding.

As a result of experimental and technological investigations, it was determined that in order to produce high-quality multipass welded joints of pipe elements of HPH spirals by welding with a consumable electrode in shielding gases based on argon, the optimum region of welding modes should have the following values of parameters: welding current — 110–130 A; operating arc voltage — 21–23 V; welding speed – 1–6 rpm, and as a consumable electrode, the electrode wire (preferably of grade Sv-08GS or Sv-08G2S) should be used with a nominal diameter of 1.0 mm, and its feeding rate should be in the ranges of 120–160 m/h.

It was also established that among many inverter-type WPS offered by the domestic market, the most rational for meeting the above-mentioned requirements is the use of inverter-type WPS MIG/MAG/TIG/MMA 303 designed and produced by «Tesla Weld» and widely spread in Ukraine, which contains in a single casing WPS and a device for automatic feeding of electrode wire MIG 303 with a standard four-roller feeding mechanism. The basic technical characteristics and VAC of this WPS are suitable for meeting the specified technical requirements with the exception of the durations of the time intervals «gas before welding» and «gas after welding». In addition, in accordance with the algorithm of operation of this WPS, the natural burning-out of the electrode wire at the completion of welding cycle and the automatic switching off of the welding current, the termination of the electrode wire feed and the switching-off of the gas cut-off (gas valve) occur almost simultaneously. To eliminate the mentioned drawbacks of WPS of the type MIG/MAG/TIG/MMA 303 (peculiar also to other analogues offered by the Ukrainian market) the development of WCCU and modernization of a control system for this WPS were made at the SEC WCNPE.

The manufacture and testing of the mock-ups of WCCU units and modernization of WPS control system of the type MIG/MAG/TIG/MMA 303 allowed establishing that in such variant, this modified WPS, preserving all the technical characteristics peculiar to it, is capable to provide the execution of the welding cycle shown in Figure 2. Here the range of control of the duration of the «gas before welding» time interval amounts at least from 1.0 to 10.0 s, and the range of control of the duration of the «gas after welding» time interval is not less than from 10.0 to 30.0 s.

In order to simplify the connection of the components of technological equipment for mechanized (automatic) welding of pipe elements of HPH spirals to the power mains, providing the ability of executing the mode «emergency stop» at the operator's command or automatically with almost instantaneous and complete deenergizing of all these components without exception, and introduction of their additional automatic protection against long-term overload by current consumption and from a stable short-circuiting, USPE was developed and designed at the SEC WCNPE.

Conclusions

1. The mechanized arc welding in a mixture of gases is the most efficient and rational method of multipass welding, i.e. with consumable electrode for use in manufacture and restoration repair of HPH.

2. The basic requirements to technological equipment for mechanized welding of butt joints of pipe elements of HPH spirals, and also the region of basic optimized parameters of welding mode with a consumable electrode in a mixture of shielding gases (with solid electrode wire of predominantly grade Sv-08GS or Sv-08G2S with a nominal diameter of 1.0 mm). At the same time, it was established that two welding passes are enough to produce quality welded joints of pipe elements of HPH spirals.

3. The technical proposals for creation of a complex of the technological equipment for mechanized (automatic) welding of rotary joints of pipe elements of HPH spirals were developed.

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