APPLICATION OF AUTOMATIC ORBITAL WELDING IN MANUFACTURE OF HOUSINGS OF NEUTRON MEASUREMENT CHANNELS OF NUCLEAR REACTORS

N.M. MAKHLIN[1], **V.E. POPOV**[1], **N.S. FEDORENKO**[1], **A.V. BURBA**[1], **V.M. PYSHNY**[2], **V.A. DYUKOV**[3] and **V.B. GONTAREV**[3]

[1]SE REC WCPE of the E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: techno@paton.kiev.ua
[2]SE NNEGC «Energoatom»
3 Vetrova Str., 01032, Kiev, Ukraine. E-mail: 1.kizmenko@direkcy.atom.gov.ua
[3]SS «Energoeffektivnost» of NNEGC «Energoatom»
59 L. Tolstogo Str., 01032, Kiev, Ukraine. E-mail: ee@eff.atom.gov.ua

Up to present time neutron measurement channels were mainly delivered in Ukraine from abroad. Therefore, problem of improvement of operating characteristics and mastering of domestic production of such channels is highly relevant. Application of automatic non-consumable electrode orbital welding was considered for obtaining of welded joints of elements of housings neutron measurement channel of being one of the most important elements of the system of in-pipe measurements of nuclear power units. Results of working through of technology of automatic GTA welding and optimum modes of performance of these joints using domestic modernized automatic machines for orbital welding ADTs 627 U3.1 and ADTs 625 U3.1 as well as technical characteristics of indicated automatic machines are given. Procedure of assembly for GTA welding of structural elements of housings of neutron measuring channels was described. Results of non-destructive testing, mechanical testing, metallographic investigations and tests to intercrystalline corrosion resistance of welded joints are submitted. It is shown that application of developed technologies and equipment allows mastering the domestic production of neutron measurement channels. 10 Ref., 3 Tables, 3 Figures.

Keywords: *automatic orbital welding, neutron measurement channels, nuclear reactors, spigot-and-socket joint, non-consumable electrode*

One of the main directions of development of modern nuclear power units (NPU) is intensifying of nuclear and heat processes by means of increase of neutron-flux density, temperature and pressure of coolant [1–3]. At the same time, the problems of increase of operating resource of NPU and providing of measures of safety and trouble-free operation are set that causes rise and complication of requirements to functional reliability and life time of systems of measurement, manipulation, protection and control of nuclear reactors being designed, constructed and under operation.

Light-water thermal neutron based reactors (PWR and BWR type), in which water is used as a coolant and moderator, obtained the highest application in world power engineering. Not less than 87 % of power units of nuclear power plants (NPP) of the whole world [1, 2] refers at present time to power units with such reactors. Tank water-water power reactors (WWER) being in operation at all 15 power units of four active NPP of Ukraine can also be related to reactors of PWR type. The same reactors are supposed to be used in future in development of new power units of Ukrainian NPP.

On-line inspection of reactivity and energy-release on height and radius of core in the WWER reactors is carried out by systems of in-pipe measurements, the most important elements of which are the neuron measurement channels (NMC) being immersed in the core (points of immersion are located on cross section). For example, application of 58–64 NMC is provided for the most wide-spread rector WWER-1000.

NMC is a helium-filled long-length (12.14 m) cylinder hollow hosing, inside the immersion part of which 7 neutron and from 1 to 3 (in some modifications of NMC) temperature detectors are installed.

Structurally NMC housing consists of nozzle *1*, penetration *3* and two transition inserts *2* and *4*, forming assembly part, as well as body *5*, pipe (or two pipes) *6*, *7* and tip *8* relating to immersed part of the housing (Figure 1). These elements of NMC housing have different external and internal diameters and being joined into single-

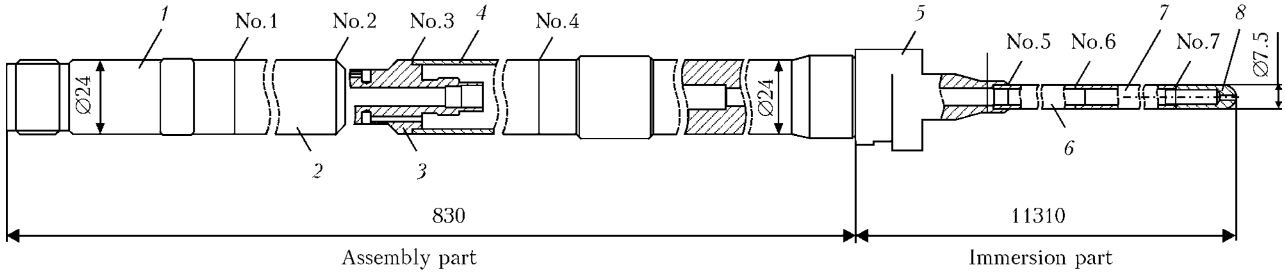


Figure 1. Scheme of NMC housing (for designations see the text)

structure of the housing with the help of welded joints.

Peculiarity of operating conditions of NMC in WWER-1000 reactors is simultaneous effect of neutron irradiation as well as high pressure (15.7–17.7 MPa) and temperature (330–350 °C) of environment. This predetermines the main requirements to NMC housing structure, its elements and welded joints, i.e. resistance to stress-corrosion cracking; vacuum tightness of welded joints and their mechanical strength (breaking force according to the existing requirements of not less than 4905 N or 500 kgf); life time of NMC — not less that 4 years (operating life of not less than 40,000 h). Mentioned requirements provide for application of 08Kh18N10T chromium-nickel steel of austenite grade (0.08C; 18Cr; 9Ni; 0.6Ti) as a structural material of NMC housing and all its structural elements.

Up to present time NMCs were delivered in Ukraine mainly from abroad, therefore, problem of improvement of their service characteristics (first of all safety indices) and mastering of domestic production of such channels is sufficiently relevant.

One of the possible ways of solution of this problem is an industrial application of technology of performance of welded joints of NMC housings by means of non-consumable orbital position butt welding in inert gases (GTAW) and technological fixture for realizing of these processes developed at SE Research-and-Engineer Center of Welding and Control in Power Engineering of Ukraine (REC WCPE) of the E.O. Paton Electric Welding Institute of the NAS of Ukraine together with Separated Subdivision «Energoeffektivnost» of SE NNEGC «Energoatom» (SS «Energoeffektivnost»).

Elaboration of GTAW technology for joints of elements of NMC housing was carried out using serially manufactured modernized automatic machines ADTs 627 U3.1 and ADTs 625 U3.1 for orbital position butt welding of pipelines [4] developed in REC WCPE, the specifications of which are given in Table 1.

Automatic machines ADTs 627 U3.1 and ADTs 625 U3.1 for orbital welding were made on a similar hardware basis, namely specialized multifunctional welding power source ITs 616 U3.1 of chopper type, control system consisting of controller block ITs 616.20.00.000 and remote control panel (operator panel) ITs 616.30.00.000 as well as ADTs 625.07.00.000 collector. The difference between the automatic machines lies only in welding heads of captive type ADTs 627.03.00.000 and ADTs 625.03.00.000, respectively.

Design of these automatic machines in operation mode «Setting» allows performing adjustment operations (regulation of extension of non-consumable electrode and its spatial orientation) before welding, choosing control method («Manual» or «Automatic»), preliminary setting of values of all main parameters of mode and cycle of welding.

In operation mode «Welding» they provide the set parameters of welding cycle in continuous mode, step-pulse or modulated current welding mode.

One of the peculiarities of modernized automatic machines ADTs 627 U3.1 and ADTs 625 U3.1 lies in that a control system of these automatic machines allows carrying out arc passes, following the first circumferential, preliminary continuously adjustment and setting (program) of $(0.5–1.0)I_w$ and $(1.0–2.0)v_w$ values (where I_w is the welding current, v_w is the welding speed) set after the first circumferential pass, that not only expand the technological capabilities of indicated automatic devices, but also allow efficiently performing the processes of multi-pass welding by means of autoshaping method or subsequent penetration.

Figure 2 shows an example of sequence diagram of GTAW process in continuous mode during performance of two circumferential arc passes (ADTs 625 U3.1 automatic machine was used).

The next peculiarity of modernized automatic machines ADTs 627 U3.1 and ADTs 625 U3.1 is that the control system allows automatic backspacing of direction of movement of face chuck of welding head in completing of each (except for the last one) or first two passes at more than two circumferential arc passes.

Table 1. Main technical characteristics of automatic machines ADTs 625 U3.1 and ADTs 627 U3.1

Parameter	ADTs 627 U3.1	ADTs 625 U3.1
Diameter of pipes being welded, mm	7–24	18–42
Smallest inter-pipe distance, mm	58	72
Ranges of welding current regulation, A:		
lower value	not more than 8	
upper value	not less than 260	
Ranges of arc voltage regulation, V	7–24	
Accuracy of maintaining of set value of welding current in oscillations of supply mains in the range of ±15 % of nominal and disturbances along arc length not more than ±2.5 mm from set value, %	±2	
Accuracy of maintaining of set value of arc voltage, V	±0.20	±0.15
Ranges of regulation of rotation speed of welding head face chuck (welding speed), rpm (m/h)	0.3–10.8 (0.42–15.2; 1.36–48.8)	0.5–10.0 (1.7–33.9; 4–79)
Number of arc circumferential passes	1–4	
Nominal diameter of tungsten electrode (VL, BI or BT type), mm	1.6	2.0; 3.0
Largest radial movement of torch, mm	15	16
Largest movement of torch across the butt, mm	±1	±5
Ranges of duration regulation, s:		
gas blowing	5–25	
smooth rise of welding current	1–5	
«preheating» of welding place	1–5	
smooth drop of welding current	1–5	
Regulation of arc length	Mechanical follower	Automatic arc voltage regulation

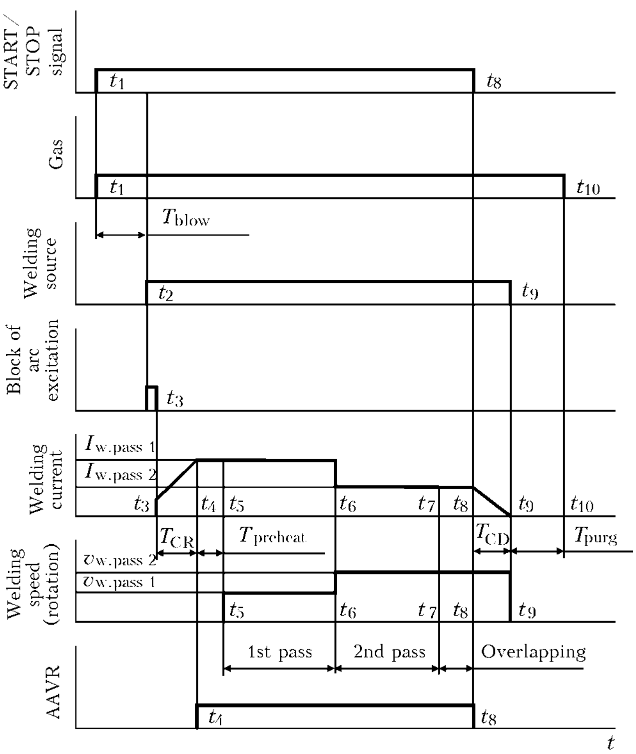
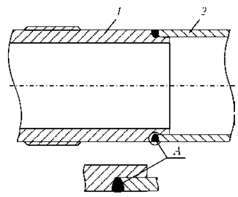
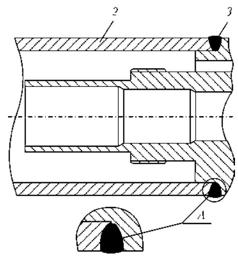
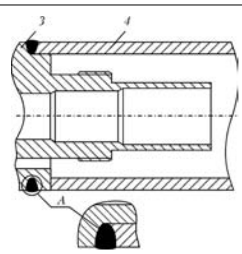
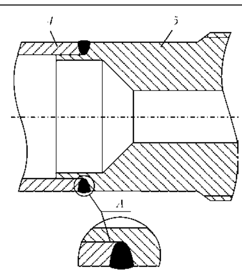
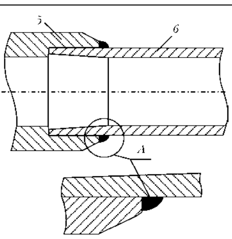
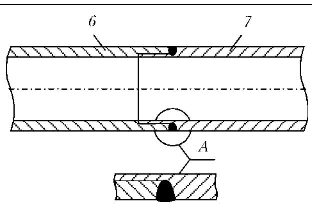
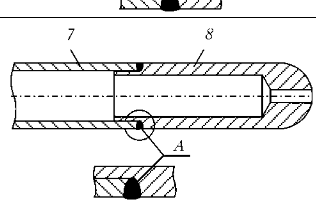


Figure 2. Sequence diagram of GTAW: T_{blow} – interval of time «gas before welding»; T_{CR} – duration of smooth rise of welding current; $T_{preheat}$ – interval of time of «preheating»; T_{CD} – duration of smooth drop of welding current («welding of crater»); T_{purg} – interval of time «gas after welding»

Besides, modernized automatic machines have one more peculiarity, namely capability to maintain the preliminary set values of parameters of welding mode having the most significant effect on quality of welded joints (welding current, arc voltage, speed of welding) in the process of welding with accuracy not worse that ±2.5 %.

Elaboration of technology for GTAW of joints of elements of NMC housing was carried out considering an experience of development of similar processes and their commercial application in manufacture of absorber inserts of containers of spent fuel storages [5] as well as earlier performed investigations in area of physical-chemical fundamentals of GTAW of thin-walled bodies of rotation [6, 7]. As a result the main factors making influence on quality of welded joints were found, determinative parameters of GTAW process of butt joints of thin-walled tubes were stated, ways for determination of ranges of welding modes providing high weld quality [8] were proposed and the most rational types of welded joints were recommended. Analysis of results and recommendations of these investigations, accumulated experience of application of GTAW of thin-walled parts, structural peculiarities of NMC housing and its elements and requirements made to them allowed making a conclusion that

Table 2. Schemes of assemblies of joints of NMC housing elements for GTAW

Joint	Type of joint
Nozzle *1* — insert *1* (weld No.1)	
Insert *2* — penetration *3* (weld No.2)	
Penetration *3* — insert *4* (weld No.3)	
Insert *4* — body *5* (weld No.4)	
Body *5* — pipe *6* (weld No.5)	
Pipe *6* — pipe *7* (weld No.6)	
Pipe *7* — tip *8* (weld No.7)	

the spigot-and-socket type joints are the most reasonable for manufacture of NMC housing. Considering this, welded joints of NMC housing elements (see Figure 1), i.e. nozzle *1* with insert *2* (weld No.1), penetration *3* with insert *2* (weld No.2) and insert *4* (weld No.3), insert *4* with body *5* (weld No.4), pipe *6* with pipe *7* (weld No.6) and pipe *7* with tip *8* (weld No.7), were worked though as spigot-and-socket ones and joining of pipe *6* with body *5* (weld No.5) as a lap joint of different thickness parts.

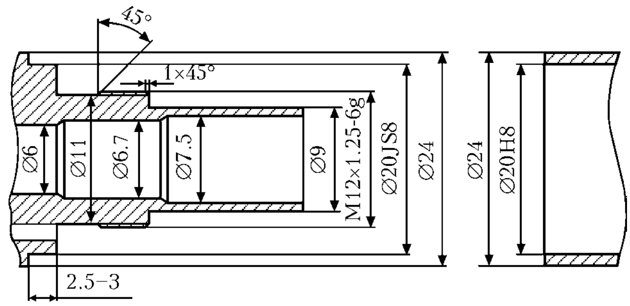


Figure 3. Scheme of joint preparation of NMC housing elements (weld No.3) for GTAW

Ranges of optimum values of GTAW modes for joints of NMC housing were determined through performance of several series of test welding on full-size specimens (models) of elements of NMC housing. All the specimens were degreased during preparation to welding and joint assembly for welding was carried out in accordance to schemes, given in Table 2 and Figure 3; at that tight fit (class III, accuracy degree 8) of mating parts was provided.

Welding of joints of specimens of NMC housing elements was carried out with variation of main parameters of welding mode (welding current, arc voltage and length, welding speed) and parameters of welding cycle (time intervals «gas before welding», «preheating», «gas after welding»; duration of smooth of rise and drop of welding current), as well as consumption of inert gas (argon), corresponding to GOST 10157.

Test welding was carried out using welding head ADTs 627.03.00.000 in order to determine the ranges of optimum values of parameters of GTAW modes for joints of pipes between themselves (weld No.6), pipe to tip (weld No.7) and pipe to body (weld No.5). At that welding of weld No.6 was performed at normal orientation of axis of non-consumable electrode to longitudinal axis of butt joint, welding of welds Nos. 7 and 5 — at certain shifting (up to 0.5 mm) from the butt axis and electrode incidence at 15° angle (relatively to normal line) in the direction of lager heat sink in accordance to recommendations of [5, 7].

Welding head ADTs 625.03.00.000 with normal orientation of axis of non-consumable electrode to longitudinal axis of butt joint was used

Table 3. Main parameters of modes and cycles of single-pass GTAW of joints of NMC housing elements

Parameter	Joints of NMC housing elements						
	Nozzle–insert (weld No.1)	Insert–penetration (weld No.2)	Penetration–insert (weld No.3)	Insert–body (weld No.4)	Body–pipe (weld No.5)	Pipe–pipe (weld No.6)	Pipe–tip (weld No.7)
Diameter of tungsten electrode, mm	2.0				1.6		
Welding current, A	65–80				25–28	11–15	18–20
Arc voltage, V	9.0–10.5						
Arc length, mm	1.0±0.1						
Welding speed, m/h (rpm)	22.60–31.65 (5.66–7)				12.0–14.3 (8.5–10)	11–15 (7.8–10.6)	12–14.3 (8.5–10)
Duration, s:							
gas blowing	5–10						
smooth rice of welding current	1.0±0.2						
«preheating» of welding place	0.8±0.1				0.70±0.05	0.40±0.05	0.60±0.05
drop of welding current	4.0±0.5						
gas purging	8–18						
Consumption of shielding gas, l/min	6–7						
Note. Grade of tungsten electrode: VT, VI, VL on GOST 23949–80 or Abicor Binzel WT, WR, Wr-2D.							

for test welding of specimens of the rest joints of NMC housing.

Quality of joints obtained as a result of test welding was evaluated by means of non-destructive testing methods (visual-measurement method and leakage tests) as well as with the help of mechanical tests, metallographic investigations and tests to intercrystalline corrosion (ICC) resistance. Visual-measurement testing was carried out in accordance to normative documents [9] currently in force in area of power engineering with the help of micrometer gage, lens, binocular microscope (magnification 8–10) and corresponding templets. Leakage test was performed with the help of mass spectrometer and helium leak detector PTI-10 using method of vacuum chamber in accordance to the requirements and procedure given in [10]. Mechanical tests were carried out based on GOST 1497 on machine of ZDM-10 test type for spigot-and-socket joint of NMC housing with the smallest cross-section over the base metal (weld No.6).

It was determined as a result of the mechanical tests that breaking force for this joint makes not less that 4807 N (490 kgf) at penetration depth 40–50 % and not less than 11380 N (1160 kgf) at 90–100 % penetration depth. Metallographic investigations were carried out on macrosections (cut out from joints obtained by test welding) using metallographic microscope with 50–100 magnification. At that, depth of penetration, presence in metal of such defects as non-metallic inclusions, pores, wormhole and lacks of fusion, structure of weld metal and HAZ, dimensions of austenite grains were determined. Tests to ICC resistance of weld metal and HAZ were carried out on AMU method (GOST 6032).

Performance of several series of test welding of joints of elements of NMC housing, comprehensive quality testing of these joints and system analysis of obtained results allowed determining that constantly high quality of welded joints of elements is achieved in single-pass GTAW (values of the main parameters of welding modes and cycles should correspond to given in Table 3). It was also stated that feeding of inert gas (argon) inside the housing is necessary to be provided in performance of GTAW of any from indicated joints. Method for removal of such visible defects of welds as partial lack of penetration, single pores, unallowable nonuniformity of penetration (caused, mainly, by deviation of requirements on quality of preparation and assembly of parts for welding) was worked as well. It lies in performance of the second pass with the lower (in comparison with the first pass) values of welding current or with the higher welding speed.

Besides, it should be noted that presence of pipe-pipe joint (weld No.6) in NMC housing structure is not necessary. It should be performed only in the case of absence of one-piece pipe delivery.

«Energoeffektivnost» developed a set of technological fixture for providing of possibility of performance of GTAW of joints of NMC housing elements (in determination of ranges of optimum values of welding mode and cycle parameters). Testing of GTAW processes of NMC housing elements developed in REC WCPE on full-size models (experimental specimens) of NMC housings was also carried out in this organization under conditions close to industrial one. It showed that constantly high quality of welded joints is achieved in application of developed technology.

Conclusions

1. Technology of single-pass GTAW of joints of thin-walled different thickness bodies of rotation using ADTs 627 U3.1 and ADTs 625 U3.1 automatic machines for orbital welding was developed. It provides performance of high-quality spigot-and-socket joints of NMC housing elements.

2. Commercial application of developed GTAW technology and means of technological fixture allow manufacturing NMC and similar parts at domestic enterprises in volumes necessary for power engineering.

1. Cameron, I. (1987) *Nuclear reactors*. Moscow: Energoatomizdat.
2. Shirokov, S.V.(1993) *Physics of nuclear reactors*: Manual. Kyiv: Vyshcha Shkola.
3. Trofimov, N.A., Lappo, V.V. (1979) *Measurement of parameters of thermophysical processes in nuclear power engineering*. Moscow: Atomizdat.
4. Makhlin, N.M., Korotynsky, A.E., Bogdanovsky, V.A. et al. (2011) Single- and multioperator systems for automatic welding of position butt joints of nuclear power plant piping. *The Paton Welding J*., **11**, 28–36.
5. Bogdanovsky, V.A., Gavva, V.M., Makhlin, N.M. et al. (2011) Application of automatic orbital welding to fabricate absorbing inserts for spent nuclear fuel storage containers. *Ibid*., **12**, 34–37.
6. Ishchenko, Yu.S. (2002) Physical-technological principles of weld formation in arc welding process. In: *Welding in nuclear industry:* Transact. of NIKIMT. Moscow: IzdAT, Vol. 2, 204–240.
7. Bukarov, V.A. (2002) Technology of automatic shielded arc welding. *Ibid*., Vol. 1, 149–210.
8. Poloskov, S.I., Bukarov, V.A., Ishchenko, Yu.S. (2000) Influence of parameter deviations of argon-arc position butt welding on quality of welded joints. In: *Proc. of All-Russian Sci.-Techn. Conf*. (Moscow, Sept. 2000). Moscow: MEI, 22–25.
9. *PN AE G-7-016–89*: Unified procedure of control of base materials (semi-products) of welded joints and surfacing of equipment and pipelines of nuclear power plant. Visual and measuring control. Moscow: Energoatomizdat.
10. *PN AE G-7-019–89*: Unified procedure of control of base materials (semi-products) of welded joints and surfacing of equipment and pipelines of nuclear power plant. Control of tightness. Gas and liquid method. Moscow: Energoatomizdat.

Received 27.03.2013