SINGLE- AND MULTIOPERATOR SYSTEMS FOR AUTOMATIC WELDING OF POSITION BUTT JOINTS OF NUCLEAR POWER PLANT PIPING

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The paper describes PWI activities on development and manufacture of orbital complexes for automatic welding of butt joints of 8–76 mm piping. These complexes became accepted for repair of equipment of power units of Ukrainian nuclear power plants.

Keywords: *arc welding, TIG welding, non-consumable electrode, filler wire, position butt joints of pipelines, single- and multioperator systems, automatic welding, control systems*

Piping of NPP reactors is the basic element of NPP production strings [1]. According to the norms and rules of nuclear power engineering, the piping, operating predominantly under the conditions of exposure (in many cases simultaneously) to high temperatures, residual stresses and higher pressure of corrosive-aggressive heat carrier, are classified as a separate group of devices by their impact on NPP reliability and safety [1, 2]. Functions, performed by NPP power unit piping, complexity of their service conditions, cramped conditions in welding operation sites and limited access to these areas make high demands of quality, strength and corrosion resistance of welded joints on such piping [1–3]. Labour consumption for welding butt joints of NPP power unit piping is equal up to 40 % of all the labour consumption in NPP mounting and up to 60 % of total labour consumption for welding operations in reactor mounting. The main scope of the work (up to 80 %) is taken up by welding of butt joints of less than 100 mm diameter piping. Up to 60 % of the total number of butt joints are those of austenitic steel piping [1, 4, 5].

The majority of welded joints of NPP power unit piping are position butt joints, for which the dominating welding processes are manual argon-arc (TIG) welding using filler material, and automatic non-consumable electrode orbital welding (GTAW) with filler wire feeding or without it.

Manual TIG welding using filler material is characterized by relatively high technological flexibility that made this process accepted in mounting and particularly in repair of NPP power unit piping. Multioperator welding systems (MWS) are mostly used to perform manual TIG welding of piping and other reactor equipment, and much more seldom it is performed with single-operator specialized TIG welding machines. On the other hand, manual TIG welding has a number of significant disadvantages:

- involvement of a large number of highly qualified welders for performance of a considerable volume of welding operations in compressed terms (for instance, in mounting of just one power unit with WWER type reactor it is necessary to perform welding of not less than 41,000–60,000 butt joints of not more than 100 mm diameter piping) [5];
- required level of welded joint quality is not achieved, which results in their defect level reaching 15–45 % at first-attempt acceptance that necessitates repair of defective butt joints and in this connection, the inevitability of significant additional losses [4–6];
- machine time in TIG welding of piping butt joints (arcing duration) is usually equal to not more than 20 %, that does not allow reaching the required efficiency of the welding station [6].

Unlike manual TIG welding, the process of automatic orbital GTAW ensures:

- stable high quality and operational reliability of piping welded joints (at GTAW without filler wire the defect level at first-attempt acceptance does not exceed 4 %, that with filler wire — 7 %);
- not less than 4 times increase of welding operation efficiency;
- considerable reduction of duration of operator training in automatic welding (several months) compared to duration of training of a highly qualified welder in manual TIG welding (several years) [4–7].

Experience of operation of welded joints made with orbital automatic machines ODA (developed by R&D Institute of Mounting Technology — NIKIMT) on water and steam-water service lines of RMBK-1000 rectors, which have long ago passed the limit of their design service life without a single repair, provides convincing proof that the greatest effect from application of GTAW process is achieved as a result of many times reduction of the cost of repair of piping welded joints during their operation [7].

GTAW process using orbital complexes of ODA series and other models developed by NIKIMT, was applied with greatest success in mounting and repair of piping of NPP power units with channel reactors of RMBK type, the level of welding operation automation reaching 60 % [1, 4, 6, 7].

At present in Russia, Ukraine and in a number of other countries NPP power units are being constructed and will be constructed in the near future mainly with reactors of WWER and BN type, in mounting of which the level of automation of piping welding does not yet exceed several percent, that is attributable to a number of objective and subjective causes. These include absence or incomplete sets of modern orbital automatic machines, designed for typesizes of piping applied in the structures of local NPP power units, as well as equipment, devices and fixtures for sound preparation of piping butts for GTAW; established technologies of mounting up to 100 mm piping, according to which such piping in the absence of their working drawings, is mounted to suit job, without enlarging them into blocks; limited application of such advanced technologies of piping mounting as pack and cassette mounting methods, preliminary binding of the mounted heat engineering equipment by piping, etc., which make application of GTAW of site butt joints the most effective; absence of commercial production of GTAW equipment, designed for power supply from systems of centralized power supply of welding stations, widely used in mounting [1, 4, 5, 8].

Welding equipment market now offers a wide range of orbital automatic welding machines, developed and manufactured by foreign companies, for instance, POLYSOUDE (France), ESAB (Sweden), etc. They, however, require considerable operating costs, and, in the opinion of leading specialists in the field of automatic orbital welding, are markedly inferior to even earlier developed by NIKIMT automatic machines (for instance, ODA series) as to machine time resource, suitability for dimensions and interpipe spacing in local power units, technological capabilities (welding tube butt joints of thin-walled small diameter piping by the methods of autopressing or sequential penetration still have not been mastered in foreign countries), method of torch assembly cooling (all foreign models of orbital automatic welding machines envisage liquid cooling), repairability of automatic machine components [1].

Considering the scale of development of nuclear power engineering through upgrading and extension of residual life of operating and construction of new NPP power units with WWER type reactors, application of GTAW to perform more than 120,000 piping welded joints in each power unit appears to have no alternative, while development and mastering of commercial production of modern local orbital automatic welding machines, particularly for welding small-diameter piping (up to 100 mm), and fitting the mounting organizations and repair units of NPP with such automatic welding machines and equipment for edge preparation are becoming ever more urgent tasks.

Single-operator ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1 automatic machines, developed at PWI, allow solving a certain part of these tasks. These machines are designed for orbital TIG welding without filler wire of position butt joints of piping of 8 to 76 mm diameter with up to 4 mm wall thickness from steels of austenitic or pearlitic classes or high alloys under the conditions of mounting and repair of power engineering facilities, including NPP and TPP, as well as in other industries.

The main technical parameters of ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1 automatic machines are given in the Table, and block diagram of automatic machines is shown in Figure 1. Each of the semi-automatic machines includes multifunctional power source ITs 616 UZ.1 for TIG welding, controller block (control system) ITs 616.20.00.000, remote control panel (operator panel) ITs 616.30.00.000, one of welding heads ADTs 627.03.00.000, ADTs 625.03.00.000 or ADTs 626.03.00.000, respectively, and ADTs 625.07.00.000 manifold.

ITs 616 UZ.1 power source ensures:

• formation of vertical («bayonette») external volt-ampere characteristics (VAC) necessary for the process of TIG welding;

• presetting of welding current values and time components of welding cycle by welding current and inert gas feed (duration of time intervals of «gas-to-welding», «smooth increase of welding current», «preheating», «smooth decrease of welding current», «gas after welding»);

• contactless excitation of welding arc by high-voltage breakdown of the arc gap;

• stabilization of set values of welding current and time parameters of welding cycle at the impact of external disturbances (mains voltage fluctuations, arc gap length variation, etc.);

• possibility of realization of the modes of automatic step-pulse welding, manual and automatic welding by modulated current, as well as cycles of welding in modes 2T, 4T and in special 4T-1 mode;

• possibility of remote control.

Power unit *1* (see Figure 1) of the power source includes power isolating transformer and power low-voltage rectifier, adjustable DC step-down converter (DC-DC converter) and welding current sensor. The main component of DC-DC converter control path is PWM-controller *2*, to the control input of which a signal proportional to welding current setting voltage comes from control unit *3*, while the signal proportional to welding current comes to its information input. Welding current is regulated by variation of setting voltage (setting), welding current and voltage being related by a straight linear dependence. Stabi-

Main technical characteristics of ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1 automatic machines

Parameter	ADTs 627 UZ.1	ADTs 625 UZ.1	ADTs 626 UZ.1
Welded piping diameter, mm	8–24	18–42	42–76
Range of welding speed regulation, m/h	1–20		
Tungsten electrode diameter (VL, VI or VT grades), mm	1.6	2.0; 3.0	
Greatest radial displacement of the torch, mm	15	16	20
Greatest displacement of the torch across the butt, mm	±0.1	±5.0	
Torch cooling	Gas		
Range of welding current adjustment, A	8–250		
Range of arc voltage adjustment, V	9–18		
Accuracy of welding current maintenance, %, not worse than	±0.2		
Accuracy of maintaining arc voltage, V, not worse than	±0.20	±0.15	
Position of electric drive of faceplate rotation	Parallel to pipe longitudinal axis		
Radius of rotating parts, mm, not more than	60	65	80
Method of arc length stabilization	Mechanical follower	ARAV	
Number of arc passes	1–4		
Weight of welding head, kg, not more than			
Consumed electric power (at welding current of 250 A), kV·A, not more than	5.7		

lization of this welding current value is ensured at the expense of application of negative feedback by welding current.

Control block *3* of welding power source generates signals which are used to control switching on and automatic switching off of arc excitation block *4* of the power source; generation, adjustment and maintaining during welding the assigned values of all the settings and time parameters of current component of welding cycle for welding process modes and stages; control of gas equipment *5* of the power source that ensures control and adjustment of time parameters of gas component of welding cycle; generation of control signals required for functioning of welding cycle controller *7* included into the automatic machine control system.

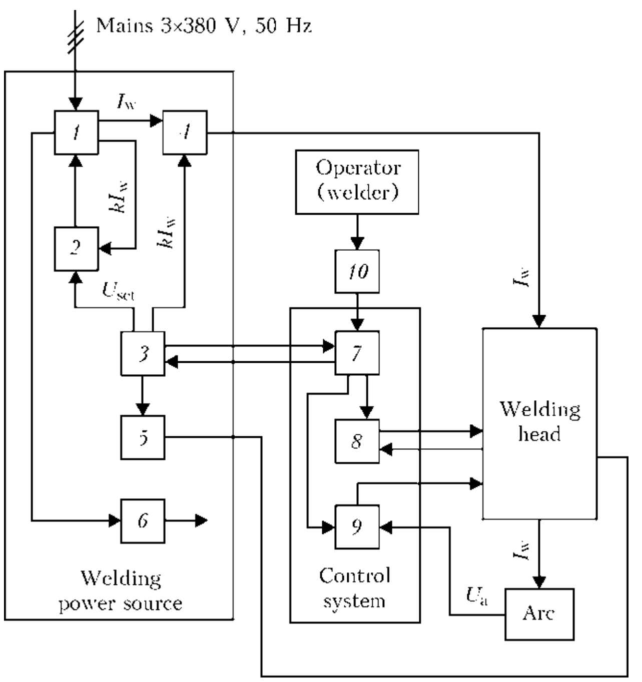

Figure 1. Block-diagram of orbital automatic machines ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1: *1* — power unit of welding power source; *2* — PWM-controller; *3* — control block of welding power source; *4* — arc excitation block; *5* — gas equipment; *6* — control circuit power unit; *7–9* — controller of welding cycle, rotation drive and ARAV, respectively; *10* — remote control panel (operator panel)

Arc excitation block *4* is a voltage booster, with its output circuit connected in series into the welding circuit between the output of power source power unit *1* and electrode of the torch, mounted in the head of automatic welding machine, and is designed for generation of high voltage pulses, injected into the arc gap to perform contactless excitation of the welding arc at the initial stage of the welding process.

Power unit *6* of the power source generates stabilized and unstabilized direct current voltages, as well as decreased alternating current voltage, required for powering the control circuits, components and blocks of the power source, automatic machine control system, remote (operator) control panel, gas equipment, and welding head mechanism drives.

Power source ITs 616 UZ.1 belongs to welding power sources of «chopper» type, which have just as high dynamic characteristics and control capabilities, as the inverter-type welding power sources, the chopper-type power sources being somewhat inferior to welding inverters as to their weight and size characteristics. They, however, are significantly superior to the latter as to the characteristics of functional and service reliability and repairability. This is attributable to the fact that compared to welding inverters, chopper-type power sources are characterized by a smaller number of stages of conversion of the energy flow supplied from the mains to the welding arc, location of welding current regulator in the low-voltage part of this flow, minimizing the risk of avalanche-like development of nonrestorable failures in case of an accident.

If required, ITs 616 U3.1 power source can be effectively used for realization of the processes of manual TIG welding, also with application of modes of welding by modulated current.

Automatic machine control system is designed for:

• generation of control signals of switching on, off and duration of functioning of the automatic machine components and mechanisms, in keeping with the assigned algorithms of performance of GTAW of position butt joints of pipelines;

• ensuring regulation and processing of feedback signals and maintaining during welding the programmed values of welding speed (speed of displacement of the torch with non-consumable electrode), arc gap length and number of arc passes;

• automatic performance of changes of welding cycle parameters (welding current, welding speed, direction of rotation of welding head faceplate), depending on the number of arc pass, as well as the stage of welding cycle.

The main functional blocks of automatic machine control system are controllers of welding cycle *7*, rotation drive *8* and automatic regulator of arc voltage (ARAV) *9*.

Welding cycle controller *7* ensures assigning of time parameters of GTAW cycle, as well as values of welding current, welding speed, number of arc passes, direction of its displacement, depending on diameter, material and wall thickness of welded piping.

Rotation drive controller *8* is designed for adjustment and maintaining during welding of assigned values of speed of rotation of welding head faceplate around the piping being welded through stabilization of the rotation speed of reduction gearmotor of welding head rotation drive through feedback using signals generated by reduction gearmotor encoder.

ARAV controller *9* ensures maintenance during welding of specified value of arc gap through automatic compensation of its deviations from the programmed value by correction of the vertical position of welding torch electrode relative to the surface of welded piping. Continuous-type ARAV, applied in the automatic machine, is a closed-loop system of automatic adjustment, based on application of proportionality of arc voltage to its length in non-consumable electrode welding [9, 10].

Control system of automatic machine functions together with the remote control panel (operator panel) incorporating the control, signaling and indication elements, ensuring:

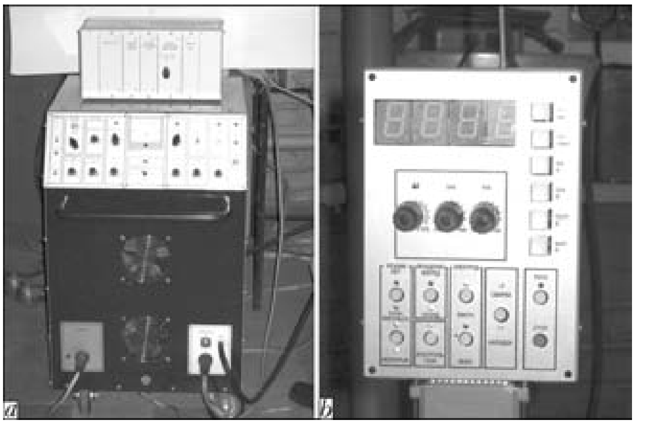

Figure 2. ITs 616 UZ.1 power source, ITs 616.20.00.000 control system (*a*) and ITs 616.30.00.000 remote control panel (*b*) of ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1 automatic machines

• selection of automatic machine operating mode;

• selection of control mode;

• selection of welding mode;

• setting the direction of rotation of welding head faceplate;

• assigning the direction of radial displacement of welding head electrode for setting up mode;

• preliminary control of inert gas flow rate;

• switching on/off of welding cycle;

• setting arc voltage;

• setting welding speed;

• readjustment of welding current during welding (by ±10 %);

• digital indication of pre-assigned and current values of welding current, arc voltage, speed of welding head faceplate rotation around the piping being welded (welding speed) and inert gas flow rate in amperes, volts, rmps and liters/minute, respectively.

Appearance of ITs 616 UZ.1 power source, control system and control panel of automatic machines ADTs 625 UZ.1, ADTs 626 UZ.1 and ADTs 627 UZ.1 is shown in Figure 2.

Welding heads ADTs 627.03.00.000, ADTs 625.03.00.000 and ADTs 626.03.00.000 for GTAW of piping of 8–24, 18–42, 42–76 mm diameters, respectively, have a design characteristic for put-on heads (Figure 3), with application of unified components and mechanisms. Head design allows performing its fast mounting on the piping being welded, removal by one welding operator and reliable fastening of the head case on the piping (that prevents its displacement as a result of jerks or vibration), and ensures the accuracy of head mounting on the piping (non-parallelism of welding head axis relative to piping radial axis is not more than 3°), reversing of faceplate rotation direction by a command from the automatic machine control system, possibility of transverse correction of torch electrode position relative to piping butt axis, laminar outflow of inert gas from the torch and reliable shielding of welding zone, fast replacement of worn tungsten electrode of the torch. Each of welding heads includes a case of lighter-weight design,

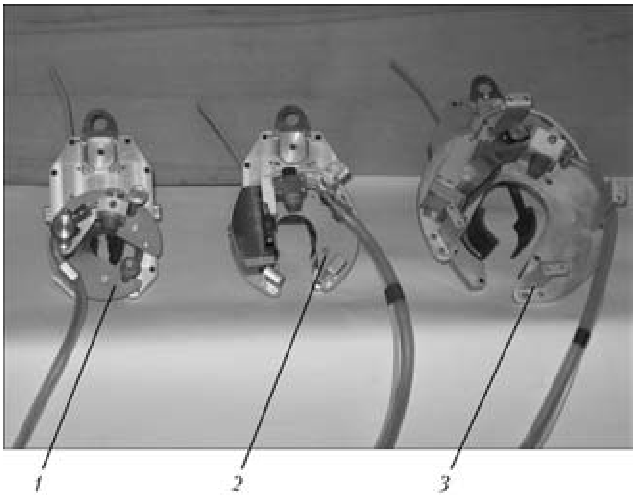

Figure 3. Appearance of welding heads: *1* — ADTs 627.03.00.000; *2* — ADTs 625.03.00.000; *3* — ADTs 626.03.00.000

mechanism of head clamping on the piping, faceplate rotating around the piping axis, mechanism of faceplate rotation (rotator), mounted on faceplate welding torch and actuator for vertical displacement of welding torch of ARAV system in ADTs 625.03.00.000, ADTs 626.03.00.000 heads and arc length stabilization system, using a follower in ADTs 627.03.00.000 head.

Stationary case of each welding head is the load-carrying structure for the mechanism of head clamping on the piping being welded and faceplate rotator. Head fastening on the piping being welded or its unfastening are performed using two clamping mechanism grips, enclosing part of the piping cylindrical surface, which are kinematically connected to the controlling lever. Faceplate rotator consists of reduction gear located inside the stationary case, and handle with built-in drive, which is a reduction gear motor with encoder. Rotator handle is parallel to piping axis, and can be fastened on the stationary case of the head in any of the two opposite directions relative to faceplate plane. Dimensions and design of the handles, as well as electric motors and encoders of rotator drives of all the heads are unified. Rotator drives of each of the heads differ just by the reduction ratio of reduction gear motors. Head rotators are made to have common kinematic diagram.

Output gear of rotator reduction gear carries a faceplate, on which ARAV actuator is mounted in ADTs 625.03.00.000 and ADTs 626.03.00.000 heads, and a lever with follower-stabilizer of arc length and torch with non-consumable electrode is mounted on ADTs 627.03.00.000 head. ARAV actuator incorporates a reversible reduction gear motor, the output shaft of which is connected through a tooth gear to a device of «screw-nut» type, the nut being built into the shoe moving along the screw. The shoe is rigidly connected to a bracket to which an insulator carrying a torch, is attached. The «ARAV–torch» assembly also includes a mechanism of transverse displacement, allowing correction of electrode position across the butt being welded.

Torches of ADTs 625.03.00.000 and ADTs 626.03.00.000 heads are completely unified in their composition and structure, and differ only by long-term protection of the ceramic nozzle. The torch of ADTs 627.03.00.000 head differs from these heads by dimensions, case shape, collet for electrode fastening and location of branchpipe in it for connection of head current and gas supply.

Any of ADTs 627.03.00.000, ADTs 625.03.00.000 and ADTs 626.03.00.000 welding heads is connected to ITs 616 UZ.1 power source, ITs 616.20.00.000 control system, ITs 616.30.00.000 remote control panel and gas supply system through ADTs 625.07.00.000 manifold, which can be removed from the head for up to 15 m distance.

ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines enable two kinds of operation modes — «Setting up» and «Welding», two control methods — «Manual» and «Automatic», and three types of welding modes — «Continuous», «Pulsed» and «Modulated welding current».

«Setting up» operation mode of the automatic machine is used for control of functioning of welding head rotator and checking its alignment, checking the trajectory of torch rotation around the butt joint of the piping being welded, checking and regulation of non-consumable electrode extension and technologically substantiated length of the arc gap, pre-setting (assigning) the rotation speed of the torch with non-consumable electrode. A feature of «Setting up» operation mode is absence of welding current in the welding circuit. In «Setting up» operation mode and «Manual» control method of the automatic machine the moments of the start and stop of the torch rotation are assigned by operator commands using «Start» and «Stop» buttons on remote control panel ITs 616.30.00.000. In «Setting up» operation mode of the automatic machine and «Automatic» control method the moment of the start of torch rotation is also assigned by the operator, and rotation stopping is automatic at the moment of completion of the set cycle duration, in keeping with the selected number of rotations and with certain «overlapping» of the section of the start of rotation.

«Welding» operation mode of the automatic machine at «Continuous» mode type allows performing all the stages of the welding cycle for all of its components while maintaining during each pass of the arc (each complete revolution of the faceplate) constant values of welding current, arc voltage and faceplate rotation speed (welding speed), set for this pass.

In «Welding» mode of automatic machine and «Pulsed» mode type the process of step-pulse welding is realized, which is performed on two energy levels of welding current, following each other with set periodicity: «high» called pulse, and «low» called pause, torch displacement (faceplate rotation) with the specified speed occurring only during time intervals, corresponding to welding current pause duration.

«Modulated current welding» mode is realized in «Welding» operation mode of the automatic machine and «Continuous» type mode, using «Modulation» mode of ITs 616 UZ.1 power source with current modulation being provided, and faceplate rotation speed during each pass being maintained constant at the level set for this pass.

To implement any of the three kinds of welding modes, it is possible to use, as in «Setting up» operation mode of the automatic machine, one of the two control methods — «Manual» or «Automatic». With «Manual» control method the start and end of the welding cycle are assigned by operator commands. With «Automatic» control method the start of the welding cycle is also assigned by the operator, while cycle completion occurs automatically, rotation of welding head faceplate being performed during time interval, the duration of which is a sum of durations of all the assigned arc passes (full revolutions of the faceplate around the piping being welded), duration of «overlapping» of the point of welding start and duration of smooth lowering of welding current («crater welding up»).

During earlier research [11, 12], it was found that in GTAW without filler wire of piping butts there exist mode regions, in which the respective relationships between welding current, arc voltage, welding speed and shielding gas flow rate provide the possibility of achieving the high and stable quality of welded joints. The same investigations have also revealed that to achieve a high quality of welds the maximum admissible deviation during welding by one of the mode parameters of GTAW of position butt joints of piping from the set values should not exceed ±14 % for welding current, ±13 % for arc voltage, ±10 % for welding speed and ±20 % for shielding gas flow rate, and at simultaneous introduction of disturbances by all the parameters of the mode the maximum admissible deviations by each parameter should not exceed ±2.5 %.

In ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines the above requirements by accuracy of maintaining during welding the assigned parameters of its mode are fully satisfied. This, as well as the circuit and design solutions incorporated into the automatic machines and their functional capabilities, allows realization of all the known technologies, including pulsed processes, GTAW of position butt joints of 8 to 76 mm piping with up to 4 mm wall thickness, as well as welding by the processes of autopressing, successive penetration and by a comparatively new process, which was called antipressing in Ukraine [12].

In 2008–2009 commercial manufacture of ADTs 627 UZ.1, ADTs 625 UZ 3.1 and ADTs 626 UZ.1 automatic machines was mastered in Ukraine that allowed beginning fitting nuclear power engineering enterprises and NPP repair units with these machines. An example of successful application of automatic machines of this series is their application in GTAW in helium atmosphere of sealing joints of a pipe with the end piece and plug (batch production at PP «Atomenergomash» of NNPC «Energoatom») of absorbers for containers of dry storage of spent fuel.

Pilot production trials of ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines showed that they can be effectively applied for GTAW of position butt joints of thin-walled piping both in repair of operating NPP power units, and in mounting of those under construction, as well as other power engineering facilities, the highest effectiveness of automatic machine application being achieved at piping enlargement into blocks.

On the other hand, wide application of GTAW in construction of power engineering facilities is restrained by a number of factors, including the features of mounting heat engineering equipment and piping of NPP power units, in particular, mounting undertime, need for concentration and simultaneous operation of tens of individual welding stations in a limited production area, specific potentially hazardous conditions of work performance, eliminating application of AC 220 and 380 V mains interconnections for power supply of welding and other process equipment [13]. This accounts for predominant application of systems of centralized power supply of manual arc (MMA) welding and manual TIG welding in mounting of NPP power units. Each of such MWS includes powerful multioperator welding rectifier with a flat external VAC, individual welding stations and main wiring connecting them. In most of the cases MMA and TIG welding modes are regulated by ballast resistances in the circuit of each individual station [9, 14]. The advantages of the existing MWS are a relatively safe voltage level in the main wiring, the value of which does not exceed the values of open-circuit voltage of multioperator welding rectifier (i.e. not more than 80 V), as well as simplicity, reliability and mobility of the welding station equipment, and its essential drawbacks are a pronounced dependence of welding current of each individual station on arc gap length and fluctuation of voltage in the mains powering the multioperator rectifier, mutual influence of welding stations at their simultaneous operation, absence of the possibility of maintaining the set parameters of process modes with the required accuracy and high power input in welding operations.

The noted disadvantages of the currently available MWS are totally absent in MWS based on electronic regulators of welding current for MMA and TIG welding, which provide not only a considerable increase of MWS efficiency (from 41 to not less than 83 % at MMA welding and from 21 to not less than 84 % in

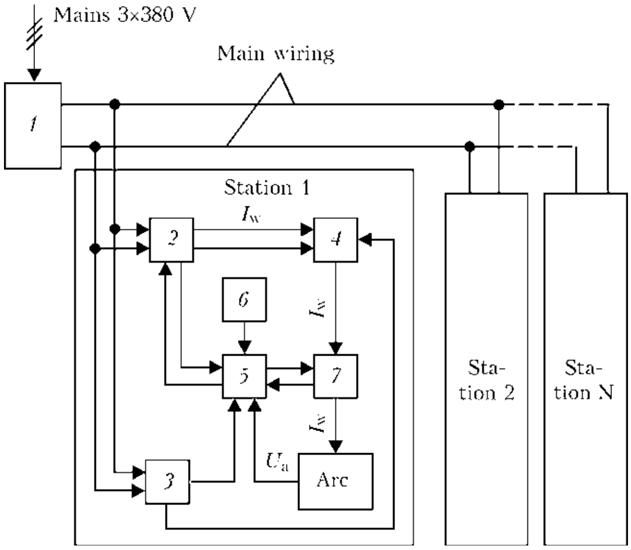

Figure 4. Block-diagram of multioperator welding system for automatic orbital welding (for designations see the text)

TIG welding), but also an essential expansion of technological capabilities, that is the prerequisite for improvement of welded joint quality [15, 16]. The properties and characteristics of welding current regulators for MWS for MMA and TIG welding enable development of MWS for GTAW of position butts of piping in mounting and repair of power engineering facilities.

One of such MWS, the block diagram of which is given in Figure 4, was developed at PWI on the base of components of ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines and upgraded welding current regulators RDG-201 UZ.1 for TIG welding.

As a centralized power source, MWS for GTAW uses multioperator welding rectifier *1* of VDM, VKSM, VMG series, or a similar one from those available, as a rule, in operating NPP and TPP power units and widely applied in mounting of the constructed power engineering facilities. Each individual station contains electronic regulator of welding current *2* and power unit of control circuits *3*, arc excitation block (AEB) *4*, control system *5*, remote control panel (operator panel) *6*, and welding head *7*, powered from the main wiring.

Upgraded regulator of welding current RDG-201 UZ.1, applied in MWS, has the same external VAC, dynamic properties and functional capabilities (except for ensuring arc excitation), as ITs 616 UZ.1 power source for TIG welding, and as to design of power components and control path RDG-201 UZ.1 welding regulator practically does not differ from DC-DC converter of power unit of this power source. Being part of MWS station equipment, welding current regulator RDG-201 UZ.1 ensures pre-setting of parameter values and realization of GTAW current and gas component in all the types of welding modes (continuous, step-pulse, modulated current welding). Technical characteristic of upgraded welding current regulator RDG-201 UZ.1 is given below, and its appearance is shown in Figure 5.

If required, welding current regulator RDG-201 UZ.1 incorporated into MWS station equipment for GTAW can be also used for manual TIG welding (for instance, for tack welding, defect repair, etc.).

Multichannel block of control circuits *3* (see Figure 4) performs conversion of main wiring voltage into stabilized and non-stabilized DC voltages required for powering arc excitation block *4*, control system *5*, remote control panel (operator panel) *6* and drives of welding head actuators *7*. Main channels of control circuit power unit are reversible step-down DC-DC converters with an increased conversion frequency (up to 132 kHz), that allowed miniaturizing their structural dimensions and weight.

AEB *4* implements the circuit of thyristor generator of high-voltage pulses with resonance pumping [9], which has the secondary winding of its output pulse transformer connected in series into the welding circuit. High voltage pulses generated by AEB cause a breakdown of the gap between the welding head electrode and surface of piping being welded, that creates conditions for excitation of a stable arc discharge in this gap.

Specification of upgraded welding current regulator RDG-201 UZ.1

Supply voltage (main wiring voltage), V	52–88
Rated welding current, A	200
Range of welding current regulation, A, not more than:	
lower value	8
upper value	260
Greatest deviation of welding current from specified value at supply voltage fluctuations (main wiring voltage) up to ±25 % of rated 70 V value, %, not more than	2
Range of regulation of the duration, s:	
smooth increase of welding current	1–5
«preheating» of welding area	1–5
pulses (pauses) of welding current in the mode of modulated current welding	0.10–2.25
smooth decrease of welding current («crater» welding up)	1–5
gas purging («gas-to-welding» time interval)	5–25
gas blowing («gas-after-welding» time interval)	5–25
Efficiency (at rated welding current), %, not less than	80
Overall dimensions, mm, not more than	515 × 281 × 353
Weight, kg, not more than	24

Used as control system *5*, operator panel *6* and welding head *7* of MWS station equipment are ITs 616.20.000 control system, ITs 616.30.00.000 control panel, and depending on diameter of welded piping, one of welding heads ADTs 627.03.00.000, ADTs 625.03.00.000 or ADTs 626.03.00.000.

Upgraded welding current regulator RDG-201U Z.1, control system ITs 616.20.00.000, control panel ITs 616.30.00.000 and manifold for connection of the welding head service lines, included into the composition of MWS station equipment for GTAW, are designed as monoblock structures with the control circuit power unit built into the control system structure, and AEB and inert gas flow meter are built into the manifold structure. To ensure compactness and mobility and ease of station equipment operation and storage, one of the possible design solutions can be placing and fastening the welding current regulator and control system in a mobile structure, which is an equipment rack fitted with wheels.

Maximum length of welding circuit for individual MWS stations for GTAW and automatic machines ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1, which ensures a sound process of automatic orbital welding of position butt joints of piping, is equal to 60 m.

A feature of MWS for automatic orbital welding is the possibility of simultaneous operation of individual stations for GTAW and manual TIG welding stations under the condition that the load current of multioperator welding rectifier does not exceed the admissible value, here both electronic regulators and ballast resistances can be used at manual TIG welding stations for welding current adjustment.

Loading capability of multioperator welding rectifier, when using ballast resistances as station regulators was determined from relationship [9]

$$N = \frac{I_{2\mathrm{r}}}{k_0 I_{d\,\mathrm{r}} \sqrt{\mathrm{DC}/100}}, \qquad (1)$$

where N is the greatest number of stations, which can be connected to multioperator rectifier; $I_{2\mathrm{r}}$ is the rated secondary current (load current) of multioperator rectifier; k_0 is the coefficient of simultaneous operation of stations; $I_{d\,\mathrm{r}}$ is the rated welding current of the individual station; DC is the duty cycle of individual station, %.

When electronic regulators of welding current are used in MWS, the loading capability of multioperator rectifier is determined by the following formula [16]:

$$N = \frac{\eta I_{2\mathrm{r}}\, U_{2\mathrm{r}}}{k_0 I_{d\,\mathrm{r}} U_{d\,\mathrm{r}} \sqrt{\mathrm{DC}/100}}, \qquad (2)$$

where η is the efficiency of electronic regulator; $U_{2\mathrm{r}}$ is the rated secondary working voltage of multistation rectifier; $U_{d\,\mathrm{r}}$ is the rated arc voltage (welding voltage).

If MWS includes both additional stations with electronic regulators of welding current, and stations with ballast resistances, determination of loading capacity of multioperator rectifier is performed by the following expression:

$$N = \eta\, \frac{(I_{2\mathrm{r}} - nI^1_{d\,\mathrm{r}})\sqrt{\dfrac{\mathrm{DC}}{U_{2\mathrm{r}}}}}{k_0 I_{d\,\mathrm{r}}\, U_{2\mathrm{r}} \sqrt{\dfrac{\mathrm{DC}}{100}}}, \qquad (3)$$

where n is the number of stations with ballast resistances; $I^1_{d\,\mathrm{r}}$ is the rated welding current of the station with ballast resistance.

Figure 5. Appearance of welding current regulator RDG-201 UZ.1 for TIG welding

Comparative characteristics of loading capacity of MWS can be illustrated by the following example. When MWS uses multistation welding rectifier VDM-1001, in which rated secondary current $I_{2\mathrm{r}}$ = 1000 A and rated secondary voltage $U_{2\mathrm{r}}$ = 60 V, at k_0 = 0.65, rated welding current of individual station $I_{d\,\mathrm{r}}$ = 200 A and 60 % duty cycle, loading capacity is equal to:

• 10 TIG or MMA welding stations for the variant of application of ballast resistances as station welding current regulators;

• 26 stations for manual TIG welding or GTAW with application of electronic regulators of welding current;

• 10 manual TIG welding or GTAW stations in the case when MWS composition includes 4 stations with ballast resistances and 6 TIG welding or GTAW stations, if MWS incorporates 5 stations with ballast resistances.

CONCLUSIONS

1. Development and mastering of commercial production of ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines for orbital welding without filler wire allows fitting mounting organizations and repair units and enterprises of power engineering industry by modern local equipment, which enables realization of both well-established and new technologies of automatic welding of position butt joints of thin-walled piping of 8 to 76 mm diameter from steels of austenitic and pearlitic classes and high alloys in mounting and repair of power engineering facilities.

2. Application of commercially produced electronic regulators of welding current in MWS not only significantly widens the technological capabilities, and improves the technico-economic characteristics of such systems, but also is the necessary condition for con-

struction of MWS for automatic orbital welding, in particular by upgrading the currently available MWS, thus opening up the prospects for a considerable increase of the level of automation in welding position butt joints of piping in mounting of the constructed power units of NPP, TPP and repair of operating ones, as well as other major power engineering facilities.

3. Achievement of a high level of unification of components of ADTs 627 UZ.1, ADTs 625 UZ.1 and ADTs 626 UZ.1 automatic machines for GTAW and use of these components in MWS station equipment for automatic orbital welding enable effective and flexible operation of such automatic machines, narrowing the range and reducing the number of equipment units, required for fulfillment of welding operations in mounting and repair of power engineering facilities, lowering of operating costs for this equipment, and acceleration of personnel training.

4. Further development of single- and multioperator systems for GTAW is expansion of their functional and process capabilities by improvement of control system of automatic machines and MWS station equipment at the expense of development of a bank of typical welding modes and application of microprocessors and non-volatile memory.

In conclusion the authors believe it to be necessary to note that development and design of the above single- and multioperator systems for automatic orbital welding was performed with active and direct participation of engineers V.Yu. Buryak, N.S. Fedorenko, V.L. Kobryansky, A.G. Skirta, E.V. Kunkina, D.S. Oliyanenko, retrofitting of GTAW technologies and developed of equipment — engineers V.M. Gavva, A.D. Cherednik, A.V. Tkachenko, and mastering of this equipment production — engineers O.I. Korkach, V.N. Andrejchenko, V.E. Ivanov, A.U. Mnukhin, V.P. Tishchenko, G.I. Pisarev, V.M. Zolotov, V.S. Pavlovsky.

1. Grinenko, V.I., Roshchin, V.V., Khavanov, V.A. et al. (2008) To problem of automation of site welding of nuclear power plant pipelines. *Tekhnologiya Mashinostroeniya*, **8**, 48–51.
2. *PN AE G-7-008–89*: Rules of design and safe operation of equipment and pipelines of nuclear power plants.
3. *PN AE G-7-009–90, PN AE G-7-010–90*: Equipment and pipelines of nuclear power plants. Welding and surfacing. Fundamentals.
4. Belkin, S.A., Shefel, V.V. (1985) Automatic argon-arc welding in mounting of nuclear power plant piping. *Energ. Stroitelstvo*, **11**, 43–46.
5. Galyshev, V.K. (1988) Application of automatic welding in mouting of piping of Zaporozhskaya nuclear power plant. *Ibid.*, **3**, 9–10.
6. Belkin, S.A. (1988) On progress of mechanized welding program of butt joints of pipelines of up to 150 mm diameter. *Ibid.*, **3**, 3–4.
7. Shefel, V.V. (1988) State-of-the-art and prospects of development of small-sized pipe-welding equipment. *Ibid.*, **12**, 3–4.
8. Sidorenko, V.F., Kuskov, M.F., Zubova, N.F. (1988) Improvement of mobility of automatic pipe-welding machine. *Ibid.*, **6**, 42–43.
9. (1986) *Arc welding equipment*: Refer. Book. Ed. by V.V. Smirnov. Leningrad: Energoatomizdat.
10. Gladkov, E.A. (2006) *Control of processes and equipment in welding*: Refer. Book. Moscow: Akademiya.
11. Poloskov, S.I., Bukarov, V.A., Ishchenko, Yu.S. (2000) Influence of parameter deviation in argon-arc welding of position pipe butts on quality of welded joints. In: *Abstr. of All-Russian Sci.-Techn. Conf. on Welding and Related Technologies*. Moscow: MEI (TU), 22–25.
12. Bukarov, V.A. (2002) Technology of automatic shielded-gas arc welding. In: *Transact. of NIKIMT on Welding in Nuclear Industry and Power Engineering*. Vol. 1. Moscow: IzdatAT, 149–210.
13. Roshchin, V.V., Khavanov, V.A., Akulov, L.I. et al. (2002) Site welding of equipment and metal structures of nuclear reactors. *Ibid.*, 81–118.
14. Bulkin, P.Ya., Donskoj, A.V. (1985) *Multistation welding systems*. Leningrad: Sudostroenie.
15. Korotynsky, A.E., Makhlin, N.M., Bogdanovsky, V.A. (2002) About design of electronic controllers of welding current for multistation welding systems. *The Paton Welding J.*, **12**, 16–24.
16. Makhlin, N.M., Korotynsky, A.E., Bogdanovsky, V.A. et al. (2004) Electronic controllers of welding current for multistation welding systems. *Svarochn. Proizvodstvo*, **5**, 13–18.