

# MODULAR DESIGN OF HIGH PRODUCTIVITY ELECTRON BEAM WELDING MACHINES

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The paper presents the results achieved in the field of actual design and technical solution of modern high-tech electron beam welding equipments in THE FIRST WELDING COMPANY Inc. The fundamental conceptual approaches to solution of modern technological complexes with application of powerful electron beam generator systems are described. The electron beam technological welding equipments are constructed modularly with special attention paid to harmonisation of hardware and software compatibility. The individual modules of technological unit are periodically innovated with respect to the progressive world trends in the field of electrotechnics, drive systems, computer control, mechanical modules and advances in vacuum technology. The contribution presents both the development of principal modules which form the core of technological welding complex such as stationary and movable electron gun, beam generation systems, vacuum chambers as well as auxiliary modules, which are adapted to the needs of modern industrial production and quality management. Among the examples, remote diagnostics of electron beam machine by web applications, module for monitoring and editing the parameters of technological process can be found. Three examples of different design of electron beam equipments are documented and described. 5 Ref., 14 Figures.

**Keywords:** *electron beam, welding machines, modular design, modules of welding equipment, remote diagnostics, monitoring process parameters*

The electron beam technologies are finding their application in industrial production already for several decades. During their utilisation they have brought about an immense merit to progress in actually all industrial branches, participating thus in excellent results that have been achieved in development of scientific knowledge and technical progress for the past 50 years. These have played irreplaceable task in recognition of space, progress in aviation transport and aviation industry, power engineering and general machine building [1]. They meet the parameters for incorporation into the group of high-tech technologies. Design of welding complexes makes use of new scientific knowledge and methods, materials and modern computer technology. An important role in their further development is played by factors such as commercial availability, high reliability, application flexibility and the fact that they are immediately applicable to direct industrial applications.

In the field of development and supply of electron beam machines, a system of modular design was developed in the FIRST Welding Company (FWC). In this system, unified modules are used as the basic building blocks. Technical criteria for functional modules or units are set to meet a specified function with high reliability, hardware and software are fully compatible with other modules and allow for work in autonomous mode. According to the meaning and technical function, modules can be divided into principal and auxiliary. The principal modules form the

core of technological welding complex and assure the primary function of equipment, namely the fabrication of welded joints of metallic materials in vacuum. The main modules comprise the power generator of electron beam, which is briefly called as a power block, electron gun, vacuum welding chamber, modules for vacuum generation in the welding chamber and in the electron gun, modules for positioning of welded parts, CNC control modules, modules for monitoring and illumination of welding process. The software is an inseparable part of technological complex. The auxiliary modules are not necessary a part of the equipment, however they fulfil an essential function in setting and monitoring of process parameters, creation of process databases, protection of welded joints against defect formation, extension of technological capabilities of equipment, allowing the remote diagnostics, prophylactics and service of the equipment, with utilization of remote approach by the aid of web applications. FWC have at present completed design of several tens unified, mutually compatible functional modules for the delivery of electron beam welding equipment. The concept of modular design allows to satisfy actually nearly all technical and technological requirements of customers in the highest quality and in the desired time terms. Some specific requirements of customers, mainly in deliveries of high productive welding equipment are prevalingly solved by the adaptation of design of a selected module with application of its conceptual solution.

**Selected modules of electron beam welding equipment.** It is impossible to present all unified modules within the extent of this contribution. The following chapter will present the significant modules of welding complexes from the production of FWC.

*Modules of beam generation system.* The powerblock belongs to the main unified modules and serves for creating the conditions for generation of electron beam and its automatic control [2]. The electron beam itself is formed in the electron gun. FWC is offering three power grades of electron beam generators with type designation PZ EB 7.5, PZ EB 15 and PZ EB 30. All power blocks grades have the same external dimensions, they differ just in internal electrical connections. They are inserted into two unified 19" racks & electronics cabinets type Schroff (Figure 1).

The first cabinet comprises a controllable and stabilized HV source serving for acceleration of electrons of electron gun. This source provides the kinetic energy to electrons, which is transferred to thermal energy after impingement on welded joint and serves thus for formation of welded joint. The second cabinet comprises the auxiliary sources which serve for heating the thermo-emission cathode of electron gun, the source of control voltage which regulates and stabilises the welding current, the source of current for magnetic beam focusing, the source system for magnetic beam deflection and a logic PLC automat for the manual and/or automatic control of powerblock operation. The powerblock type PZ EB 7.5 generates the electron beam with maximum power of 7.5 kW. At acceleration voltage of 60 kV it provides the welding current within the range from 0 to 125 mA. The powerblock type PZ EB 15 generates the electron beam with maximum power of 15 kW and with welding current value adjustable from 0 to 250 mA at the voltage of 60 kV. Maximum current of electron beam at the acceleration voltage of 60 kV can attain 500 mA. Figure 1 shows the mechanical design of powerblocks. Three power grades of powerblocks are conceptually built on the identical basis, they differ just in electronic outfit.

The high-voltage source of acceleration voltage is of inverter type and it consists of the following main parts:

- HV transformer with rectifier, filtration capacitors and measuring circuits situated in a separate vessel insulates with transformer oil.
- Medium-frequency converter with a series-parallel resonance circuit with the frequency of 20 kHz.
- Control, regulating, safety and measuring circuits.

Excitation of high-voltage transformer is realised via a medium-frequency inverter (20 kHz). In the case of this solution, the exciting signal is formed by an alternating switching of power transistors T1, T4 and

T2, T3 connected in a bridge, what forms the alternating voltage with rectangular course of constant frequency in the bridge diagonal. This voltage is connected to the primary HV winding via the serial-parallel resonance LC circuit, which ensures almost ideal harmonic course of the excitation voltage and a more efficient energy transfer. Stabilization of voltage and power regulation of HV source is solved by altered range of transistor switching, what allows a regulation intervention at the level of several milliseconds. Advantage of such a connection consists in application of a constant switching frequency of the exciting current, what allows to achieve very low ripple of accelerating voltage at suitable selection of filtration capacity of the secondary circuit. The measured value of welding voltage ripple at the nominal source power output of 30 kW and the switching frequency of 20 kHz is at the level of  $\pm 1.0\%$ . The electronic anti-discharge protection is selectable by an auxiliary module to HV source. The electric scheme of HV source type PZ EB 30 kW is shown in Figure 2.

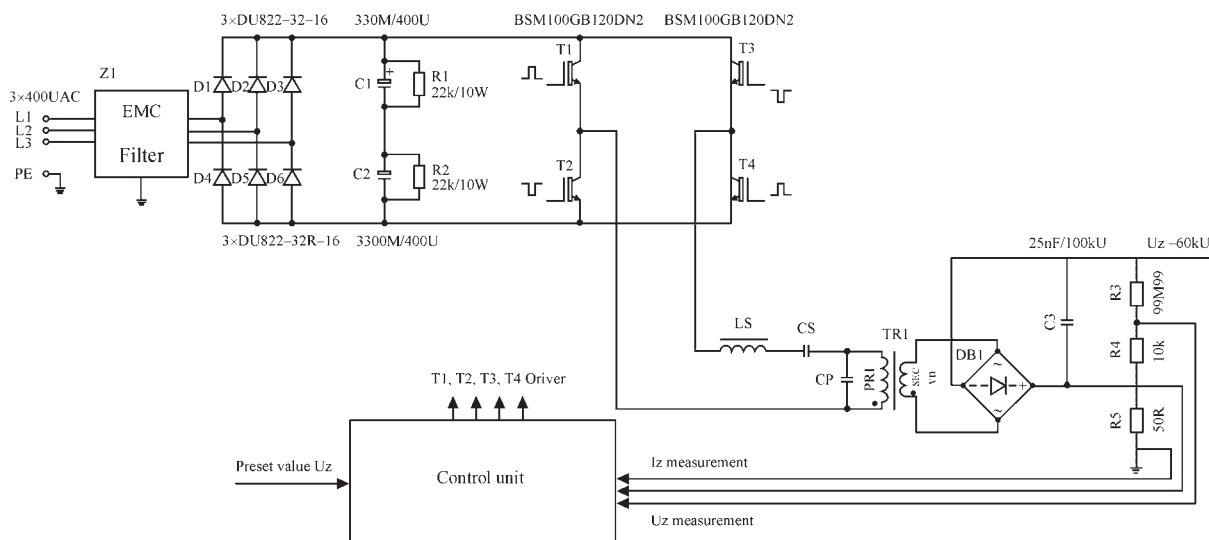
The auxiliary sources serve for generation of electron beam and the desired setting of welding parameters. These allow manual, automatic and/or program control of welding current, focusing current and electron beam deflection. The group of auxiliary sources includes the current source for filament heating, source of cathode bombarding current, voltage source for control electrode, the source of focusing current and the source for beam deflection.

#### The typical technical parameters of powerblock are as follows

Value of accelerating voltage, kV .....	controllable from 30 to 60
Maximum power of electron beam, depending on the type, kW .....	7.5, 15, 30
Stability and ripple of acceleration voltage, % .....	max $\pm 1.0$
Stability and ripple of welding current, % .....	max $\pm 1.5$
Stability of focusing current, % .....	max $\pm 0.5$

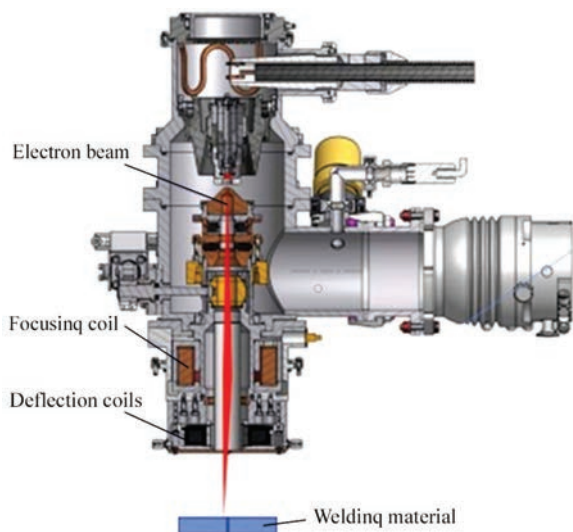


**Figure 1.** The powerblock type PZ EB 30



**Figure 2.** Electric scheme of HV source type PZ EB 30 kW

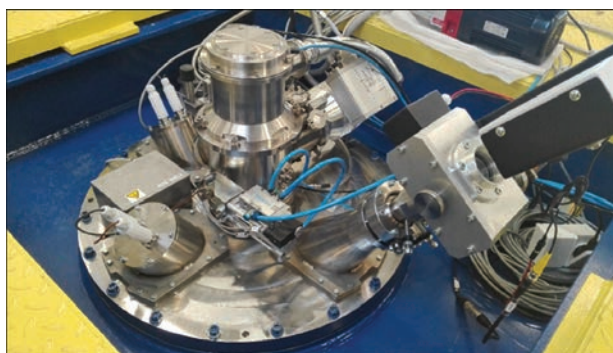
**Electron gun module.** The electron gun serves for generation, control and adjustment of power electron beam for the technological operations of welding and/or surface treatment of metallic materials [3]. It is the most important part of electron beam welding equipment. The power necessary for generation of electron beam is supplied from the powerblock. Therefore, the gun and powerblock must be mutually compatible. Modular concept recognizes the stationary electron gun working from outside at atmospheric pressure and the gun destined for applications in vacuum chamber — movable electron gun. The stationary guns are situated on the welding chamber wall to which they are tightly vacuum-proof attached. They are mostly attached to vacuum chamber statically and the welded joint is formed by programable positioning of weld joint against the electron beam. Stationary electron guns have the same design for all output power graders. An example of design of stationary gun is shown in Figure 3.



**Figure 3.** Design of a module of atmospheric gun

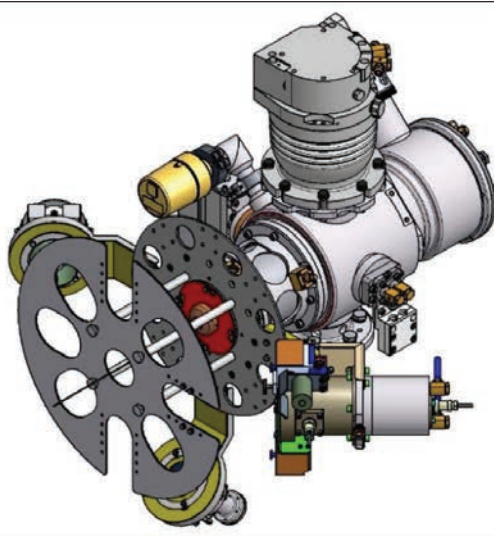
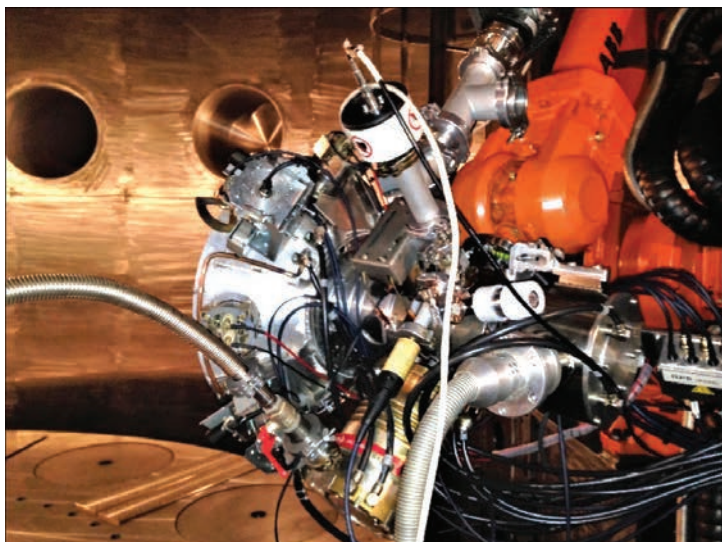
Such a gun cannot properly perform the welding operation unless it is equipped with the appropriate modules, permitting its basic functions and which enable an exact setting of electron beam on the welded joint. This is realised via auxiliary modules as the module of gun pumping to a high vacuum, module for monitoring of welding process and the module for process illumination. These modules together with the gun body are attached to a common base and create a separate unit. An example of placing the configuration of auxiliary modules on a common base with gun is shown in Figure 4.

Regarding the design viewpoint, the differences between stationary gun and movable gun for welding applications are minimum, consisting of a small deviation in sealing the inner space of the gun and the total weight. Greater differences may be observed only in the system of vacuum pumping of both guns. The atmospheric vacuum gun is pumped by a turbomolecular vacuum pump, which is additionally pumped also with a rotary vacuum pump. The movable electron gun is pumped only with a turbomolecular gun, whereas the rotary vacuum pump is unnecessary, since the vacuum is ensured by the vacuum system



**Figure 4.** Configuration of auxiliary modules of the stationary electron gun





**Figure 5.** Design of movable electron gun

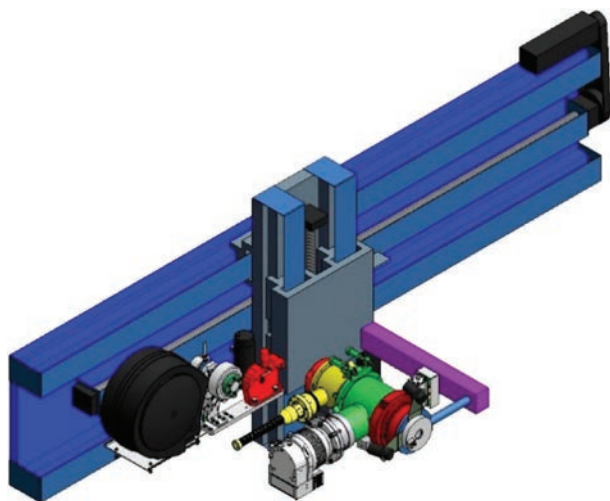
of the chamber. The design of vacuum electron gun is shown in Figure 5.

Another essential condition for correct operation of this electron gun consists in its positioning to welding trajectory in the vacuum welding chamber.

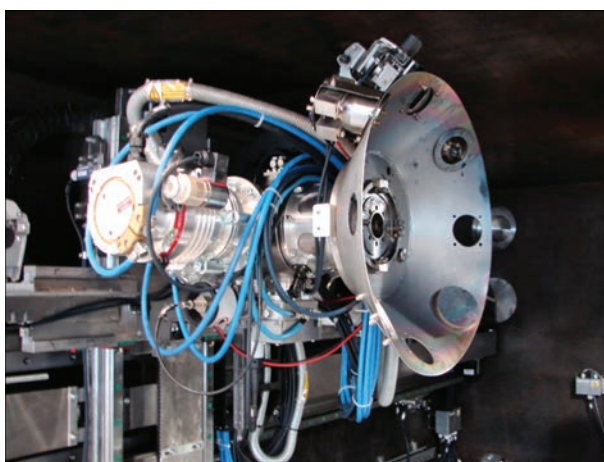
*Module for positioning the vacuum electron gun.* Two types of modules for positioning of movable electron gun in vacuum chamber are designed. These differ both conceptually and in the way of application. For the vacuum chambers of medium size, the module of two-axial positioning is designed in a Cartesian coordinate system with addition of a manual or fully automatically controlled rotary axis. Design of the two-axial module with a manual rotary axis is shown in Figure 6. The  $x$  and  $z$  axes are fully program-controlled axes ensuring the gun positioning in  $x-z$  plane. Gun tilting in rotary axis is performed manually. This system serves for fabrication of linear welds and in combination with an additional rotary positioner also for fabrication of the face and circumferential rotary welds. The presented concept allows the location of a

feed mechanism for the additive manufacturing with application of a filler in the form of wire. Practical application of this type of positioning system is shown in Figure 7.

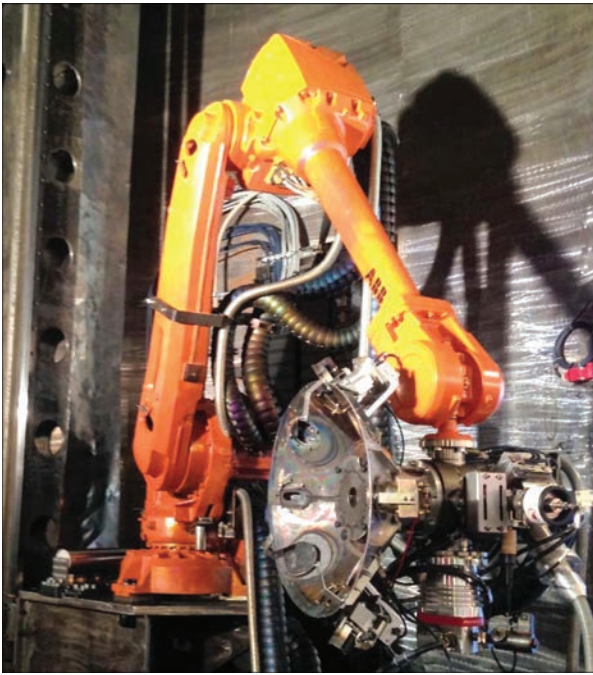
Another way of electron gun positioning in vacuum is solved with application of an adapted robotic system, modified for the operation in vacuum environment. This way of electron gun positioning is suitable for application in large vacuum chambers. Positioning of electron gun is assisted by an industrial robot type IRB 4600 in special adaptation for the work in high vacuum (Figure 8). The ABB IRB 4600 represents industrial robot with 6 axes, 45 kg carrying capacity and 2200 mm working radius. It is provided with control unit type IRC5 and RobotWare software. The robot is situated on a carriage of vertical support, which in the function of fully controlled axis allows the robot positioning in its vertical  $Z$  axis. The additional « $Z$ » axis has extended the working range of robot in  $Z$  axis to value of 8.5 m. Next additional axes  $\omega_1$  — rotation of the main positioner and  $\omega_2$  — rotation of rotation-



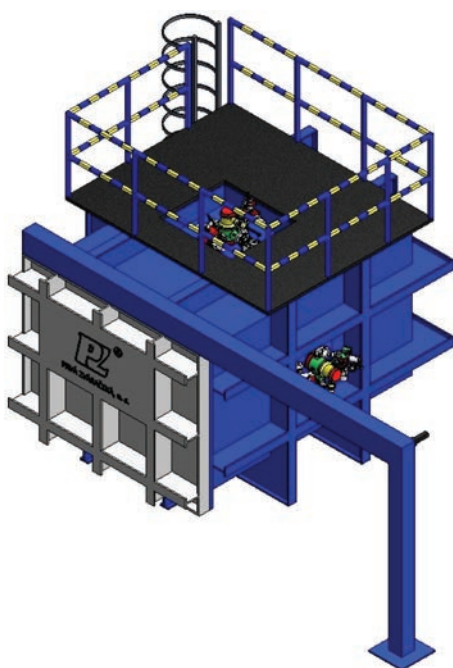
**Figure 6.** Design of a positioning module of electron gun



**Figure 7.** Practical application of a module for vacuum gun positioning



**Figure 8.** Module for vacuum electron gun positioning al nests serves for positioning of weldments. All nine axes of positioning system e.g. six robot axes and the additional three axes  $\omega_1$ ,  $\omega_2$  and  $Z$  represents fully controlled axes and can be controlled by FlexPendant unit on selecting the «technology» option from the main menu and/or by a program from the technological computer. The electron gun with monitoring is defined as the working tool EB\_GUN\_Ti. This tool has a defined mass centre of gravity and has determined the tool coordinates TCP (Tool Centre Point). RobotWare software supports all aspects of robot system, as robot motion, development and implementation of applica-



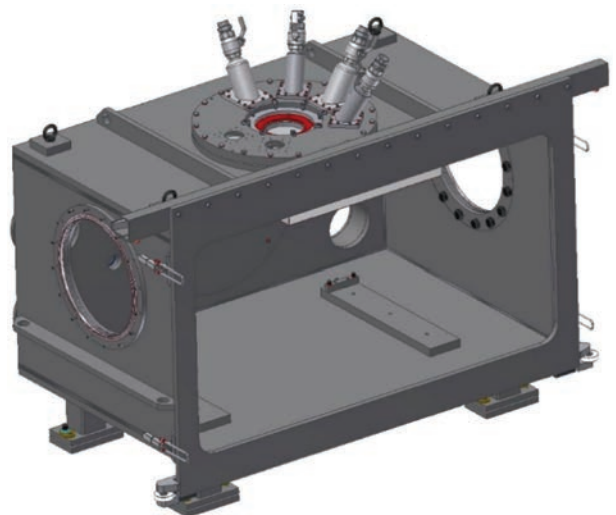
**Figure 9.** Module of a versatile chamber with the volume of 16 m<sup>3</sup>

tion programs system, as robot motion, development and implementation of application programs and communication. Communication between the control unit IRC5 and technological computer is realized through Ethernet interface. The FlexPendant controller is a portable operation unit with graphical touch screen. The RAPID programming language contains the instructions allowing the application to perform robot motions, to set the outputs and/or to read the inputs.

*Modules of vacuum chambers.* The vacuum chambers are in most cases designed by the «fitness for purpose» approach, i. e. tailored for the needs of an actual customer. The size and shape of vacuum chamber is given by the dimensions of parts to-be-welded, desired time for pumping to working vacuum and the electron gun employed. The technological preparation and manufacturing technology comprise the unifying element of modules for welding chamber design. The welding chamber must be vacuum proof, resistant against distortions and must comprise an advanced and unified system for sealing of static flanges and door systems and also for sealing of movable parts.

A versatile medium-size vacuum chamber with the volume of 16 m<sup>3</sup> may be shown as an example in Figure 9.

The welding chambers for high-productive welding must meet the condition of high efficiency. These are destined for welding of a great number of parts with identical shape and with a slight dimensional diversity. They are mostly composed of a vacuum welding chamber and one or more auxiliary chambers. Such a design makes possible that the welding chamber could be permanently pumped to the working vacuum. The auxiliary chambers ensure the operation of loading and unloading of weldments and also the operation of air intake and vacuum pumping



**Figure 10.** An example of design of welding chamber module for high-productive welding machine



of the auxiliary chamber. The proportion of net welding time during one shift against the manipulation and preparatory times is at the level of 80 %. An example of modular concept of welding chambers for the high-productive welding is shown in Figure 10 and Figure 11.

The presented examples of design of principal modules of electron beam welding equipments elucidate the concept of modular design which is applied by the FWC Inc. in design, construction and manufacture of electron beam equipment for diverse applications destined for external customers. This concept has proved as sufficiently flexible, economical and it thus creates the conditions for deliveries of equipments for the external customers in the shortest possible terms and in high quality.

*Modul for processing data collection.* This module belongs to the auxiliary modules. It can be integrated into the device upon customer request. Main function of the module is to collect all decisive welding process parameters, as the value of accelerating voltage, welding current, focusing current, welding speed, electron beam position related to welded joint etc. These and other selected parameters are recorded during the entire welding cycle. They are used for the retrospective diagnostics. The recorded process parameters are gained from the sensors of the control system and it allows simultaneous recording of more than 15 process parameter with the sampling period from 1 to 10 ms. The elaborated program allows to alter the sampling period and it also allows the collection and storage of data coming from several sources. The recorded data from individual sensors are sent in a special binary format through the communication line to the archiving computer, which assigns them the identification signs and stores them on memory media. Moreover, the program records also all binary states of the drives. The developed program for data analysis represents a browser for a huge quantity of binary data in graphical and tabular form.

*Remote diagnostics of electron beam machine by web applications.* Solution of remote diagnostics, which belongs to the next auxiliary module of electron beam welding machine, is based on special hardware and software configuration. For connecting equipment to the remote access, the industrial router from eWON company was selected and for creating a communication for data transfer between the equipment and remote user the internet service Talk2M (from the English «Talk to Machines») was utilised. These circuits are then integrated into a control system of electron beam welding machine at the customer workplace. The present state of technological solution of equipment provides the remote access to equipment



**Figure 11.** An example of design of auxiliary chamber module for high-productive welding machine

by utilising the internet and it offers the following options: Sending an alarm message in case of failure occurrence, connection of a remote visualisation, work of programmer directly in the development environment of PLC, access to archive of records of welding parameters created via a special software module for collection and analysis of processing data. The created communication channel meets all relevant safety standards, what provides a high level of protection for the transferred data against abuse.

**Examples of design of electron beam equipments.** As an example, three designs of welding equipments are shown, representing different field of industrial application of high-tech technologies from the production portfolio of FWP company, making use of electron beam technologies.

The first example is a welding technological complex with type designation PZ EZ 30 JUMBO.

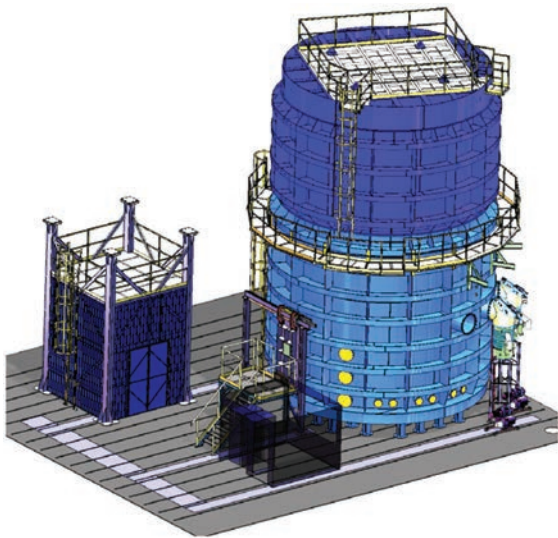
This equipment is destined for welding sizable parts in general engineering and power industry [4]. The new design of equipment employing the electron gun attached on the robot arm with integrated other two rotary and one linear axes makes possible to fabricate the rotary and linear welded joints as follows:

Rotary circumferential joints of sizable weldments on a central rotary positioner in side position as follows:

- range of weldment diameter from 500–5000 mm;
- range of weldment weight from 200 kg to 100 t;
- range of weldment height from 500–8000 mm;
- range of weld depth from 1–90 mm on austenitic steel in PC position.

Rotary circumferential welds on medium size weldments fabricated on auxiliary rotary positioners as follows:

- range of weldment diameter from 100–500 mm;
- range of weldment weight from 1–200 kg;
- range of weldment height up to 5000 mm;



**Figure 12.** The welding workplace type PZ EZ30 JUMBO

- maximum number of weldments placed in welding chamber and welded under one vacuum pumping makes 10 pieces.

Linear welds on sizable weldments fabricated on a central positioner as follows:

- range of weld length from 10–5000 mm;
- range of distance from the axis of central positioner varies within 500–2500 mm;
- range of weldment weight from 100 t to 200 kg;
- range of weld depth (penetration depth) from 1–100 mm on austenitic steel.

Linear weld of slim weldments in weight up to 200 kg fabricated on the auxiliary rotary positioners as follows:

- range of weld length from 10–5000 mm;
- range of distance from the axis of auxiliary positioner varies within 50–400 mm;
- range of weld depth (penetration depth) from 1–100 mm on austenitic steel.

The electron gun of triode type with maximum power of 30 kW is made of titanium and allows to weld the CrNi steels in thickness of 90 mm on one pass [5]. The system is provided with an electronic anti-discharge protection, monitoring module with three video cameras and laser space navigator. For

the needs of surface heat treatment and fabrication of surface layers the equipment is provided with a module for programmable beam scanning. The volume of welding chamber is 265 m<sup>3</sup> (Figure 12). The time of pumping to working vacuum of  $5 \cdot 10^{-2}$  Pa is 85 min.

The welding workplace type PZ EZ 30 TWIN-BEAM is a versatile workplace with the volume of welding chamber of 16 m<sup>3</sup>. It is destined for welding thin-walled and heavy-walled (up to 80 mm) parts in medium vacuum. Besides welding it also allows the heat treatment of surfaces of metallic materials and additive manufacturing with application of filler in the form of wire. The complex electron beam workplace is equipped with two guns, whereas it is possible to weld just with one gun or both guns simultaneously. The time of vacuum pumping to working vacuum is maximum 25 min. The vacuum chamber is equipped with the X–Y positioning table for positioning during welding, which is integrated with the system for loading and unloading of weldments to and from the vacuum chamber, a rotary positioning system and also with a wire feed unit. The overall view on the workplace is shown in Figure 13.

The welding equipment type PZ EZ ZPH may be shown as an example of a single-purpose high-productive workplace. This workplace is destined for series welding of hydromotor pistons in vacuum. The pistons of hydro-converters represent an example of extremely loaded part made of hardenable low-alloyed Cr–Mo steel. Since the steel type 42CrMo4 (1.5124) is susceptible to cold cracking, it is necessary to alter the steep thermal cycle of welding by application of preheat eventually postheat. The purpose of application of preheat/postheat is to suppress the formation of martensite in the weld metal and to ensure the formation of a tougher structure which is not susceptible to cold cracking. Possible notch effect of unsuitable geometry is eliminated by the relieving recesses under the weld root. This mechanical adaptation has allowed to dissipate the stress flow from welding, what resulted in reduced concentration of stresses in the



**Figure 13.** The welding workplace type PZ EZ 30 TWINBEAM



**Figure 14.** The welding equipment type PZ EZ ZPH



root of welded joint. Welding of hydromotor pistons in vacuum represents an ideal application of electron beam welding technology, regarding their dimensions and desired productivity, which by its nature allows to realize a controlled preheat and postheat by the same heat source which is used also for welding.

Welded joints are fabricated at the acceleration voltage of 40 kV, while the nominal power of welding equipment is 6 kW. Maximum annual production of equipment is 500 000 weldments per one shift. This welding equipment is shown in Figure 14.

## Conclusions

The aim of this contribution is to present a unified concept of design and realisation of deliveries of sophisticated technological equipments and complexes with a high degree of automation. Based on the presented results the system of modular design can be characterized as flexible and economically efficient. As the main constructional elements this system makes use of unified modules, which represent a separate functional unit which are hardware and software fully compatible with the other modules of technolog-

ical complex. This system offers a great potential of a broader application in design and construction of versatile and single-purpose equipments in the segment of general engineering.

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