DOI: https://doi.org/10.37434/tpwj2023.08.11

EVOLUTION OF ELECTRON BEAM HARDWARE FOR WELDING IN SPACE

S.O. Hlushak

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The paper deals with application of welding and conducting repair-restoration operations in space, as well as evolution of the design of electron beam tool over several decades. Technical characteristics and technological capabilities of all the generations of hardware and requirements to it at different operation stages are described. Substantiation is provided for electron beam welding being the most suitable process for application under lower gravity conditions. Specification of "Vulcan" automatic unit is given, in which welding experiments were conducted for the first time in space. Specification of the versatile hand tool (VHT) is provided, and its capabilities are described during performance of operations of welding and other related technological processes, namely cutting, brazing, coating deposition and heat treatment, if required. Samples are shown, which were made when conducting the world's first experiment in open space, when the cosmonaut-welders used VHT to perform the technological operations of welding, cutting, brazing and coating deposition. It is proved that generalization of investigation results and incorporating the experience of operation of all the previous samples of the hardware allowed development of the next "Universal" tool, which passed comprehensive testing at NASA, including in the KC-135 flying laboratory and in the space simulation test chamber. The paper presents new generation electron beam tool, which was developed and is manufactured at PWI.

KEYWORDS: space; hardware, electron beam welding, power source, automatic and manual welding

INTRODUCTION

Performance of the operations of welding and related processes in open space, which are primarily associated with metal melting, presents risks and hazards [1]. At the same time, results of the first experiments on welding in space showed which criteria should be applied for evaluation of a particular welding process. Investigations conducted at PWI starting from 1964, demonstrate that the effectiveness of the available welding processes in the space environment should be assessed using additional criteria, compared to equipment which operates on the ground. One of the main criteria is the structure material to be joined in space, and its operating conditions. Another essential requirement to the hardware for welding in space is its high reliability, simplicity and versatility. Moreover, the hardware should also meet the criteria accepted for space hardware: it should have low power consumption, minimal weight and volume of the hardware and should be safe and efficient [2].

In earlier works [1, 3] it was proved that beam welding processes are the most promising for future application in space, primarily electron beam processes, which are more efficient and have a number of significant advantages.

High energy concentration, inherent to electron beam welding, is particularly necessary for work performance in space, as it ensures minimal heat input into the metal being welded and minimal power of the entire unit. On the other hand, such a unit can be also used for cutting, brazing, and coating deposition, i.e. it has versatility highly important for space.

Investigations show that power of 1–3 kW at accelerating voltage of 10–20 kV is sufficient for performance of welding and cutting operations in space. Power to such a unit can be supplied from on-board mains of the space vehicle, or it can operate autonomously from storage batteries [3].

More over, technological hardware used in space, should have minimal overall dimensions and weight, dynamic strength, reliability, and serviceability under vacuum and at abrupt temperature changes from –120 to +120 °C [3].

"VULCAN" EXPERIMENT

Owing to many years of investigations the first automatic "Vulcan" unit was created at PWI and in 1969 it was tested in "Soyuz-6" spaceship [1, 3]. It envisaged testing the following welding processes in space: consumable electrode low pressure electric arc, low pressure plasma arc, hollow cathode and electron beam welding.

"Vulcan" unit (Figure 1) consists of two containers: unsealed and sealed one. The first unit accommodates the devices for each welding process and a turntable, which carries the samples to be welded. Low pressure is maintained in this container during operation.

The second container accommodates the power sources: autonomous battery source, secondary power source (SPS), control modules and telemetry measuring instruments. The unit is controlled from a remote panel [1].

"Vulcan" weight is approximately 50 kg. Duration of continuous operation was limited by the battery pack capacity.

Specification of "Vulcan" electron beam hardware is as follows [3]:

- electron energy of 10 keV;
- beam power of 0.6 kW;
- specific beam power of 1 kW/mm^2 at 40 mm distance from the gun edge;
- directly-heated tantalum cathode;
- diode projector;
- gun weight of 450 g; weight of high-voltage power unit with the gun of 6.5 kg.

Accelerating voltage of 10 kV was selected for performance of electron beam welding in "Vulcan" unit. A diode electron beam gun with direct heating of the cathode of 0.6 kW power and beam working current of up to 60 mA was used.

During experiment performance "Vulcan" was placed in the docking compartment of "Soyuz-6" spaceship, which was depressurized. Pressure of $<1.33\cdot10^{-2}$ Pa was maintained in it. During the experiments, the crew with the remote panel stayed in the pressurized spaceship compartment, which was separated by a closed manhole from the docking compartment [1].

Studies of weldability of aluminium alloys at welding speed of 28–36 m/h were conducted when performing the experiments. Joints of AMg6 alloy produced as a result of the experiments had much greater porosity compared to those made on the ground.

The result of the conducted experiments on electron beam welding were butt joints with and without flanging of the edges, as well as overlap joints. The following materials were used for welding: 08Kh18N10T stainless steel, VT1-0 commercial titanium and AMg6 and D20 aluminium alloys 1.5–2.0 mm thick. Also cutting of aluminium and titanium alloys, and of 08Kh18N10T steel 1.0 mm thick was performed [1].

As a result of the conducted welding operations it was established that the electron beam welding and cutting processes are stable at long-term microgravity and space vacuum. The conditions necessary for normal formation of welded joints and cuts are provided.

Consumable wire low pressure arc welding was performed to study the processes of metal melting and transfer under low gravity. Butt joints of stainless steel sheets 1 mm thick were welded on 0.5 mm substrate from the same material. However, it was not possible to produce well-formed welds, as a result of nonuniform rotation of the welding table with the samples.

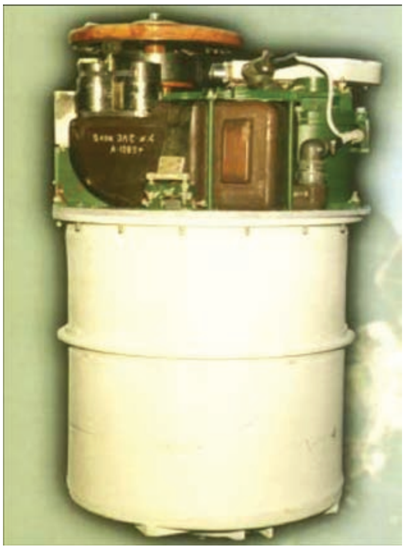

Figure 1. "Vulcan" automatic welding unit

As a result of experiment performance, it was found that the process of consumable wire low pressure arc welding in space at a high pumping down rate runs stably. A thorough study of the produced welded samples led to the conclusion that formation of a constricted low pressure arc in the vapours of the metal being welded is ensured both under the space and ground conditions. Despite certain drawbacks, experiments in "Vulcan" unit provided unique practical information, which was taken into account at development of new samples of space welding hardware.

SPACE EXPERIMENTS ON WELDING AND RELATED TECHNOLOGIES USING VHT HAND ELECTRON BEAM TOOL

The above-described hardware has remote or automatic program control. When working in open space, however, it may be necessary to perform a large number of operations (primarily, repair-restoration work or fixing large-sized structure fragments), for which it is complicated or impossible to prepare in advance. Moreover, development of emergency situations is probable, which require conducting urgent technological operations of cutting, welding or brazing, where the process and scope of the operation will be directly determined by the cosmonaut in the site of the required work performance [3].

Conducted technological experiments in "Vulcan" unit allowed developing and manufacturing a test sample of the first electron beam hand tool [3].

Experiments with the test sample for manual electron beam welding under earth gravity were conducted by PWI specialists in 1974 in space simulation test chamber using OB.1469 stand (Figure 2, *a*).

Before performance of open space experiments, the first prototype of electron beam hand tool was used to conduct numerous studies in the space simu-

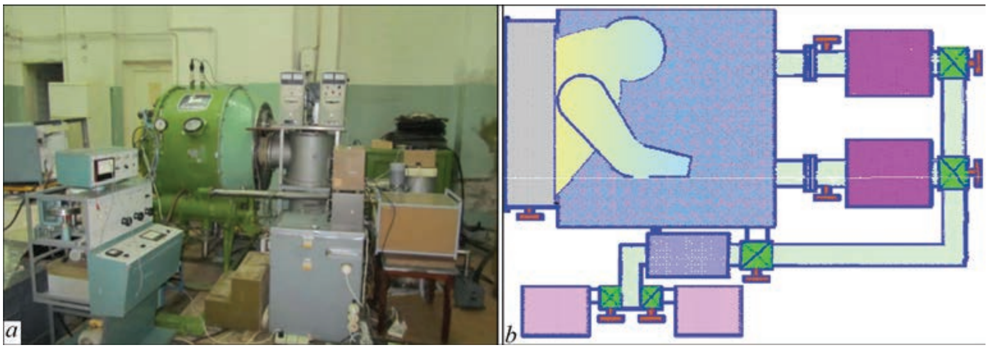

Figure 2. Hardware for conducting ground-based experiment on manual electron beam welding and cutting: *a* — OB.1469 testing stand; *b* — operator wearing a spacesuit, is under deep vacuum down to his waist

lation test chamber and in the flying laboratory under the conditions of microgravity and low temperatures.

When conducting the experiment in the chamber of OB.1469 stand, the vacuum required for electron beam operation (10^{-2}–10^{-3} Pa) was created. For these experiments a diode electron beam gun of 1.5 kW rated power with up to 15 kV accelerating voltage was developed. The operator performing electron beam welding, was wearing a fragment of the spacesuit and was in deep vacuum down to his waist (Figure 2, *b*).

The results of the conducted experiments were used to produce a flight sample of versatile electron beam hand tool VHT (Figure 3). Considering the disadvantages revealed during trials of the first prototype, in VHT the accelerating voltage was lowered to 5 kV that allowed eliminating the rigid X-ray radiation. Such an accelerating voltage and power of 0.35 kW allow conducting the technological processes of welding, cutting and brazing of 1.0–1.5 mm thick samples, as well as coating deposition in open space.

All the technological processes with VHT tool are performed by electron beam method, which is the most suitable, adaptable-to-fabrication and versatile for conducting these operations. The vacuum environment on the low earth orbit is natural and convenient for implementation of this welding process. Here, the effective efficiency of electron beam welding process is equal to 85–90 %. It allows ensuring a reliable quality of welded joints, as well as the required tightness.

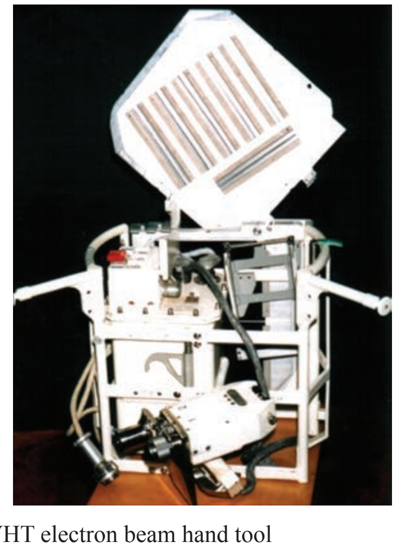

Figure 3. VHT electron beam hand tool

VHT tool is a monoblock, where the base element is a boxlike case with a special handle, made allowing for the anthropometry of the spacesuit glove. Mounted on the case front wall are two small-sized electron beam guns, each of which can form the electron beam and perform the processes of welding, cutting, brazing, as well as bombarding the crucible, while performing the coating deposition processes.

For convenience of transportation, all the functional components included into the VHT were arranged in one lattice container:

- sealed instrument compartment, containing the secondary power source, telemetry system and automatics module;
- control panel;
- cable communications.

At the container opposite side special replaceable cassettes can be fixed for performance of all the planned technological operations. Each of them carried six samples of VT1 titanium and 12Kh18N10T stainless steel for processing and joining.

VHT specification [6]:

- supply voltage of 23–34 V;
- power of up to 350 W;
- accelerating voltage of 5 kV;
- electron beam current of up to 70 mA;
- tantalum cathode of directly-heated type, 2×2 mm, $\delta = 0.06$ mm;
- VHT weight without the cassette of 30 kg;
- full weight of the cassette of 10 kg;
- weight of the tool proper of 3.5 kg.

On June 25, 1984, an experiment on performance of the technological processes of cutting, welding, brazing and coating deposition was held for the first time in the world in open space on board 'Salyut-7" orbital station, using VHT welding tool.

Samples of stainless steel and titanium alloy 0.5 mm thick were prepared for cutting. Welding and

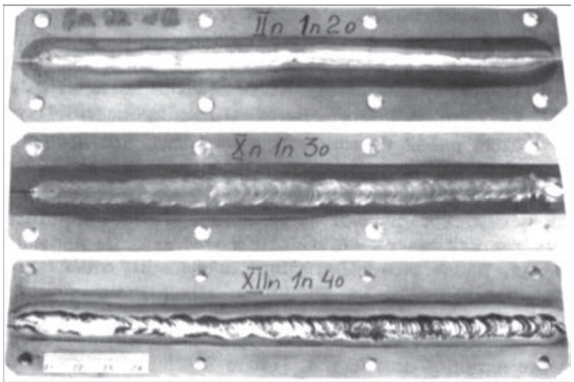

Figure 4. Samples of butt joints made in space using VHT hardware

brazing was conducted on samples from the same materials 1 mm thick. Silver coatings were deposited on blackened aluminium plates 2 mm thick of total area of 0.06 m^2 [1].

Titanium plate cutting was performed first, as the least complicated operation. This was followed by conducting the operations of welding, brazing and coating deposition. The first samples made in open space with the electron beam hand tool are shown in Figure 4. Experimental results were quite informative. First, the possibility proper of performing in open space the operations of welding and related technological processes, using the welding tool was shown; secondly, it was demonstrated that an operator wearing a spacesuit can safely conduct these technological operations and obtain good results.

After analysis of the investigation results, recommendations were developed on improvement of the procedure of ground-based training of cosmonaut-operators. The experiments were repeated in 1986, which were again performed in open space and were much more difficult. The cosmonauts conducted welding and brazing in open space of individual sections of girder structures, which were placed into special cassettes-manipulators (Figure 5). After completion of the work on deploying and folding the hinge-lever girders, the cosmonauts performed welding of the individual sections. All together, ten separate hinged sections from VT-4 titanium alloy were welded. This was followed by performance of a complex operation of welding-brazing the sections of a tube-rope girder. Each of the sections was a fragment of an open tube from 36NKhTYu steel, on which a ring from St30 steel filled with braze alloy was fitted.

Generalization of experimental results and analysis of the accumulated experience allowed formulation of the main principles of welding operations performance in space, and confirmed the need for modifying the tool, and introducing new engineering

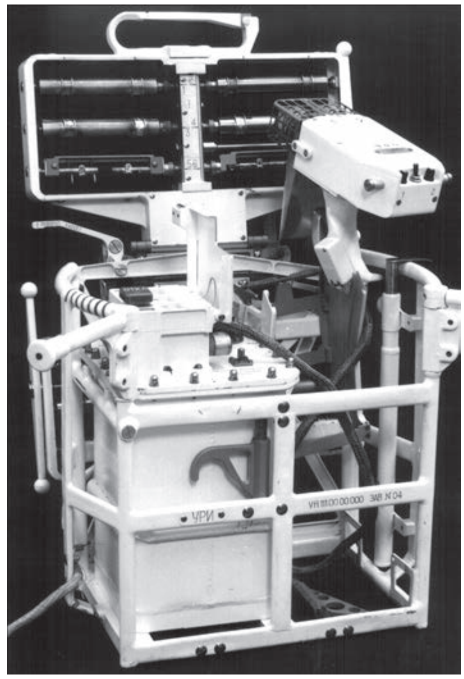

Figure 5. VHT and cassette-manipulator with installed samples of girder structure components

solutions, taking into account some essential corrections of the technological parameters.

The developers faced the following main tasks:

● bring the output power to 1 kW to work with aluminium and its alloys;

● fit the tool with wire feed mechanism;

● incorporate into the welding hardware a system of operational information and monitoring of the technological and technical parameters with the purpose of its transmission to the recording devices of the station.

"UNIVERSAL" ELECTRON BEAM TOOL COMPLEX FOR REALIZATION OF WELDING AND RELATED TECHNOLOGIES IN OPEN SPACE

Generalization of accumulated experience allowed development of a versatile set of "Universal" electron beam tool, designed for operation as part of future large-sized long-term orbital stations.

Compared to previous VHT hardware, the following changes were made in "Universal":

● hardware output power was significantly increased (2.0–2.5 times);

● the tool proper is made as functional purpose, single gun, with cathode redundancy, which allows switching from one technological operation to another one by simple replacement of the required block or fixture;

● "Universal" is fitted with the basic tool for welding, brazing and cutting, filler material feed mechanism for welding and brazing, tool with a turret at-

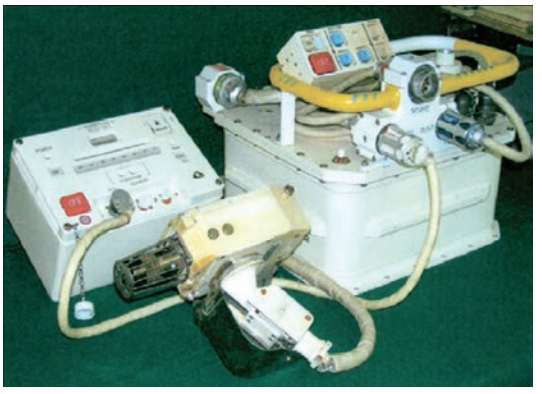

Figure 6. "Universal" hardware

tachment which has four crucibles with evaporation materials for special coating deposition.

During development of this complex the task of unifying the main functionally important components was successfully solved. Here, the maximal possible useful application of on-board power at minimal weight and size characteristics of "Universal" hardware was achieved (Figure 6). The hardware set consisted of individual blocks, which can be assembled as specialized units of different purpose and required power, if necessary. For power supply to such a unit the complex incorporates the respective high-voltage blocks and secondary power source with forced heat removal [3].

The basic tool can independently perform welding, brazing and cutting, as well as welding and brazing with filler material, using the small-sized filler wire feed mechanism. The tool has a special mechanism for coating deposition by thermal evaporation of metals, as well as a drumlike attachment with four crucibles, which allows deposition of coatings from different materials. This tool can be also used for heating the surface being treated by a defocused electron beam.

If there is a need to apply robots or manipulators for performance of mounting-assembly and repair operations, an automatic welding unit can be put together, which will include one or several (up to four) electron beam tools of up to 1.1 kW.

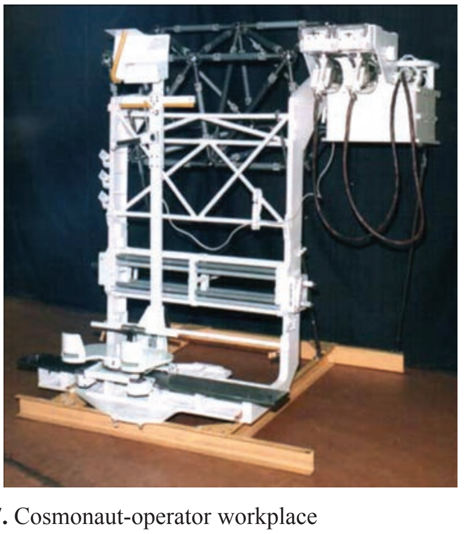

Figure 7. Cosmonaut-operator workplace

For performance of repair-restoration or mounting-assembly operations in previously unforeseen cases, a set of manual electron beam tools can be configured, which allows welding operations to be conducted directly by an operator wearing a spacesuit.

When performing this work, it is necessary to take into account the need to increase the hardware power, and to provide additional protection of the spacesuit and fitting of the cosmonaut-welder workplace, which ensures comfortable and safe working conditions for the operator (Figure 7). The workplace should be fitted with a container for storing the electron beam tool and operator panel, and it should be placed on the outer surface of the space vehicle in the area of work performance [3].

"Universal" specification:

- supply voltage of 23–34 V;
- power of up to 1110 W;
- accelerating voltage of 8–10 kV;
- electron beam current of up to 110 mA;
- tantalum cathode of directly-heated type, 2×2 mm, $\delta = 0.06$ mm.

After manufacture the "Universal" hardware was subject to multifunctional comprehensive testing. In 1991–1992 a series of tests under microgravity in KC-135 flying laboratory (L. Johnson Center, NASA, Houston), six immersions in the neutral buoyancy tank (J. Marshall Center, NASA, Huntsville) and five ascents to 6 km in the space simulation test chamber were conducted.

Qualification preflight tests of the manufactured hardware were performed with the purpose of its application during the experiment in the earth orbit [3]:

- testing for electromagnetic compatibility with the space vehicle systems;
- evaluation of hardware serviceability at long-term storage in the idle condition at temperatures of –113–+80 °C;
- thermal cycling tests (–40–+60 °C) by eight test cycles;
- toxicity tests (for toxic evolutions from space vehicle hardware);
- thermal tests;
- quantitative evaluation of spattering;
- vibration resistance testing;
- X-ray radiation measurements;
- evaluation testing for direct impact of the electron beam on materials.

After performance of comprehensive ground-based testing, "Universal" complex was recommended for use in the future orbital stations. However, in connection with problems in "Columbia" space vehi-

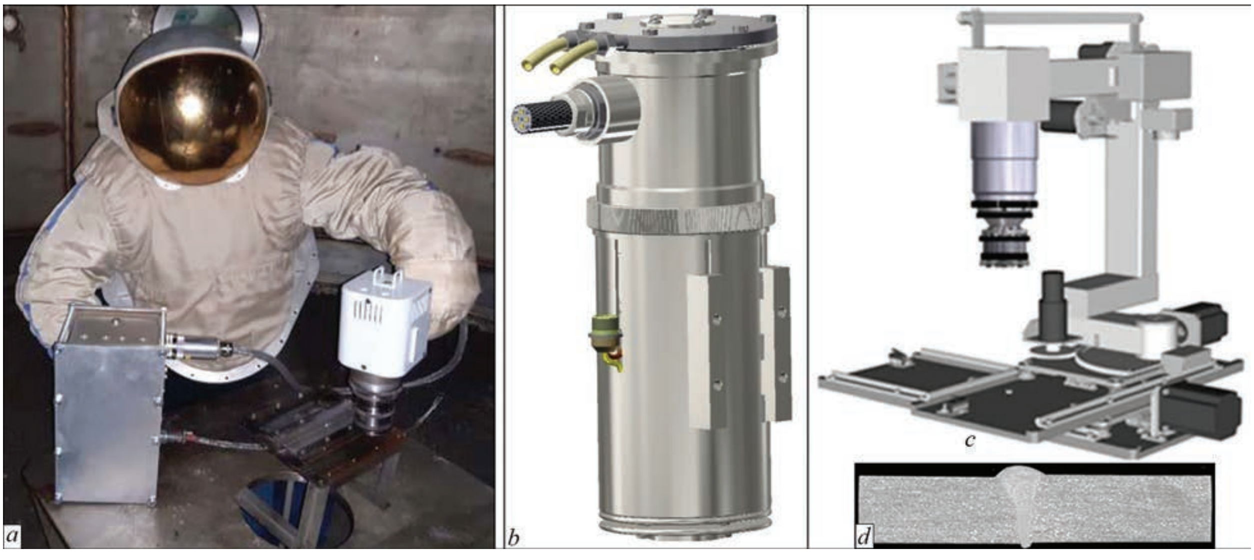

Figure 8. New generation manual electron beam tool and gun for welding and 3D printing for long-term operation: *a* — prototype of hand tool complex tested during performance of technological experiments; *b* — general view of electron beam gun for welding in space as part of a manipulator or robot; *c* — special 5-axes manipulator developed for performance of automatic welding; macrostructure of 8 mm AMg6 aluminium alloy

cle, the missions of these vehicles were discontinued, and the Program of the International Experiment with "Universal" tool was closed.

NEW GENERATION ELECTRON BEAM EQUIPMENT FOR WELDING IN OPEN SPACE

Results of experiments on automatic and manual electron beam welding conducted in open space demonstrate that the earlier developed hardware allows welding stainless steels, titanium and aluminium alloys up to 1.5 mm thick. At the same time, the thickness of material used in manufacture of sheathes of manned space vehicles is up to 4–6 mm, and the length of welds can be up to several meters [4].

Another disadvantage of previous generation gun designs is the fact that the duration of their operation is not more than 7 min, because of absence of cathode block cooling. These factors did not influence the operation of the hand tool gun. However, these factors have a negative impact for operation in the automatic and long-term mode during performance of work on 3D-printing.

In this connection it was necessary to create a new generation gun, which would have the technical characteristics for welding thicker materials, which are used in modern aerospace engineering, as well as for conducting long-term 3D-printing technological processes [5, 6]. PWI performed work on development of a new generation small-sized electron beam gun of up to 2.5 kW electron beam power. Theoretical calculations with application of the method of trajectory analysis and synthesis allowed development of an electron-optical system of the gun with improved electron beam density [7, 8], which solves the problem of welding up to 6 mm thick materials. New focusing and deflection systems were developed to enable performance of 3D-printing experiments.

Monolithic combination of the electron beam gun with the high-voltage power source was also eliminated, which promotes improvement of operating conditions of cosmonaut-operator at observation of the welding process, and allows the operator conducting the technological processes using 5 axes manipulator. The gun is connected to the power source (placed in the vacuum environment) by a flexible high-voltage cable with a high-voltage connector, and it enables the electromagnetic focusing system to form a sharp electron beam of 0.6 mm diameter. Application of such a gun design allows solving the problem of making welds of a great length.

The new electron beam gun for operation under the conditions of space has a combined system of the cathode block cooling [9]. Here, the gun duty cycle is 60 %, and the operating life is not less than 1 year, which is extremely important during performance of 3D-printing processes and conducting mounting and repair-restoration operations on the Moon surface.

Figure 8 shows a prototype of new generation electron beam gun for operation under high vacuum, temperature gradients and low gravity.

The gun design [10] also envisages use of monolithic insulators of a simplified configuration instead of brazed ones, which will be made from modern high-quality corundum materials, having higher insulation properties. Such a solution will eliminate the problems of breakdowns arising in the brazing points [11]. Filler wire feed mechanism is also envisaged [12].

CONCLUSIONS

1. Over the years of working on creation of hardware for welding in space, a whole range of hardware for technological operations performance in space has been developed, manufactured and retrofitted during operation on the ground under the conditions simulating the space environment, using the flying laboratory and in the space simulation test chamber.

2. Generalization of the results of experiments and analysis of the accumulated experience allowed defining the main principles of development, manufacture and testing of the hardware, as well as performance of welding operations in space, which determined the need to modify the hardware, and introduce new engineering solutions, taking into account some essential corrections of the technological parameters.

3. Earlier developed "Vulcan" hardware for automatic welding and VHT hand tool, which were designed and manufactured at PWI, and were tested in the space orbit, as well as the "Universal" hand tool, have such drawbacks as the short operating life of the cathode (not more then 1 h), electrostatic focusing of the electron beam (beam diameter of not less 2.5 mm at 40–50 mm working distance).

4. Taking into account the experience of operation of the previous hardware modifications, it was determined what operations should be performed by modern level hardware.

5. So far, PWI has conducted work on development of a small-sized new generation electron beam gun of 2–2.5 kW power, which allows welding up to 6 mm thick aluminium alloys.

6. It was found that the new focusing and deflection systems enable performance of experiments on 3D printing. Modern electron-optical system of the gun allows generating an electron beam of higher specific power of not more than 1 mm diameter at the distance of 50–150 mm.

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ORCID

S.O. Hlushak: 0000-0003-4518-7262

CORRESPONDING AUTHOR

S.O. Hlushak
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: electriber@ukr.net

SUGGESTED CITATION

S.O. Hlushak (2023) Evolution of electron beam hardware for welding in space. *The Paton Welding J.*, **8**, 78–84.

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Received: 13.06.2023
Accepted: 07.08.2023