HIGH ENERGY TECHNOLOGIES

ELECTRON BEAM WELDING

Studying the possibilities of electron beam welding (EBW) and the principles of construction of equipment for electron beam welding, led by academician Boris Evgenyevich Paton, began at the E.O. Paton Electric Welding Institute (PWI) in 1958. It resulted in development of the first laboratory-scale plant and welding of different small workpieces.

One year later the method of electron beam welding turned out to be in great demand: in nuclear power engineering, in production of electric vacuum devices and liquid-fuel rocket engines.

In 1961–1962 owing to effective coordination of work performed at government level, the first production machines for electron beam welding were put into operation at a number of branch enterprises. Within the next few years, application of electron beam welding became wider, first of all in the above mentioned industries, and simultaneously electron beam welding began to be accepted by aircraft and power engineering industry . In 1960-s PWI organized in Ukraine full-scale production of power units, developed by it (guns, power sources and control systems) on the basis of Sumy Factory of Electron Microscopes. 72 complete sets of power source units of SP-30 type (25 kV, 500 mA), 330 complete sets of U-250A (30 kV, 450 mA), 320 complete sets of ELA–60 (60 kV, 250, 500 and 1000 mA) and ELA-120 (120 kV, 1000 mA) were manufactured in different periods of time.

On October 16th 1969 the first test of electron beam welding and cutting of metals was carried out in «Soyuz-6» spaceship, that practically initiated the space technology. Testing was performed in «Vulkan» unit developed by PWI. Considering that in space X-radiation and difficulties with high-voltage insulation could eliminate the possibility of electron beam application, low accelerating voltage (not higher than 8 kV) was used.

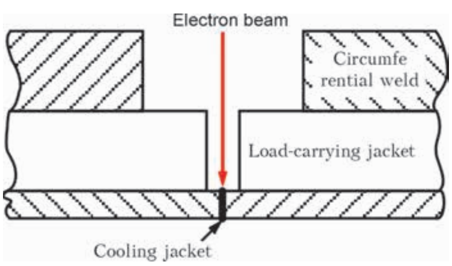
AREAS OF COMMERCIAL APPLICATION

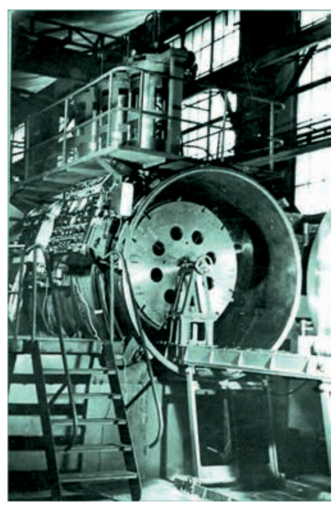
Electron beam welding of space facilities

EBW is firmly established in aerospace engineering, owing to a possibility of reducing the weight and manufacturing time of critical products. Commissioning of more than 116 machines made by industrial organizations, first of all NIITM enterprises, with PWI participation, clearly demonstrates the successful application of EBW in this industry.

Welded assemblies	Welded metals	Kind of welded joints	Number and type of machines used in aerospace engineering
Liquid-propellant rocket engines	Stainless steels, nickel-based alloys, titanium and copper alloys	Girth welds on combustion chamber bodies, valve assemblies, sprayer heads and high pressure gas guides, rotors and bodies of turbopump units	Chamber machines (32)
Fuel tanks	Aluminum alloys of Al–Cu, Al–Mg–Mn, Al–Mg–Li systems	Longitudinal welds on shells	Chamber machines (10) and machines with local evacuation of weld zone (2)
		Circumferential welds	Chamber machines (23) and machines with local evacuation of weld zone (2)
		Cut-in flanges	Chamber machines (3) and machines with local evacuation of weld zone (3)
Instrument cases	Aluminum alloys, titanium, stainless steels	Welding of flanged edges	Chamber machines (51)

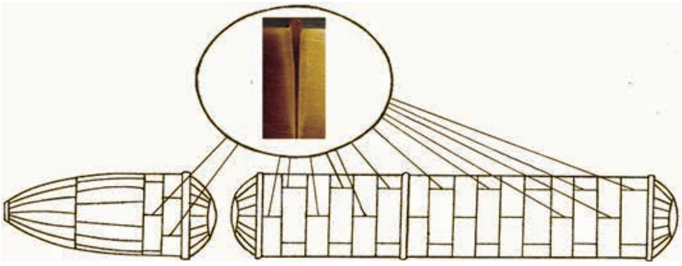
Location and layout of girth welds made by EBW on combustion chamber case of liquid-propellant rocket engine, where butt joints of dissimilar materials — copper-based alloy and steels and nickel alloys — are located deep in the technological collector. This collector has the depth of 20 mm and width of 2–3 mm, and in argon arc welding, the collector width cannot be less than 5–6 mm, this substantially decreasing the strength and reliability of shells of liquid-propellant rocket engine (LPRE).



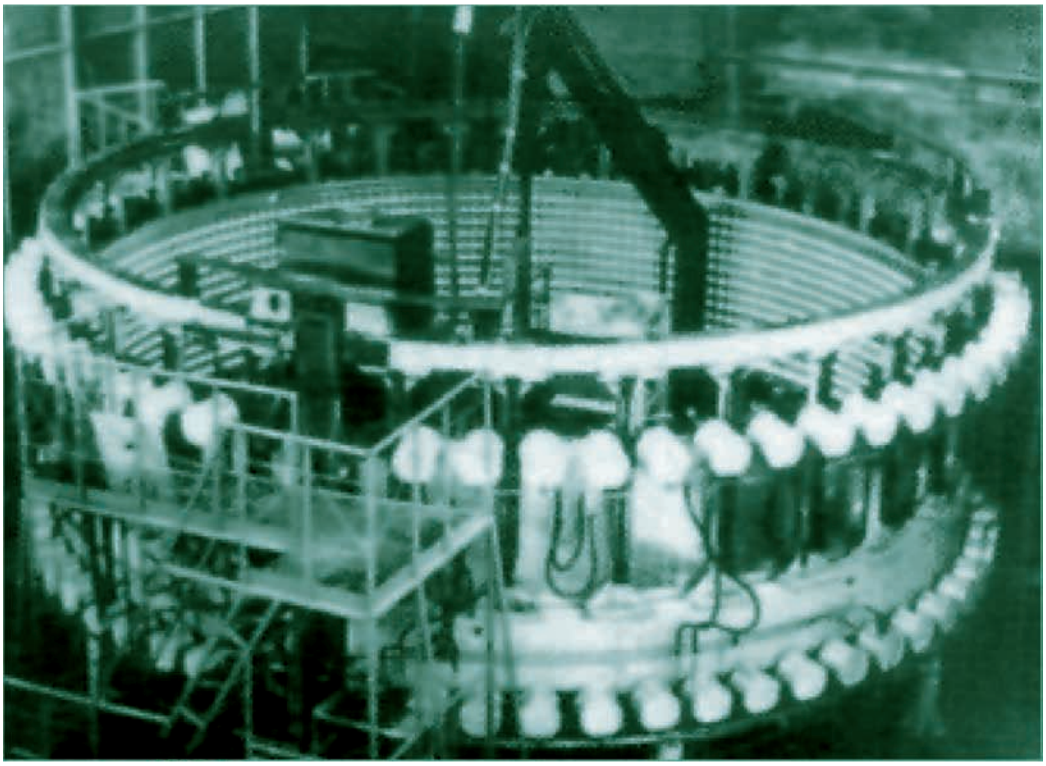


General view of the first production machine U-86 developed at PWI for EBW of combustion chambers

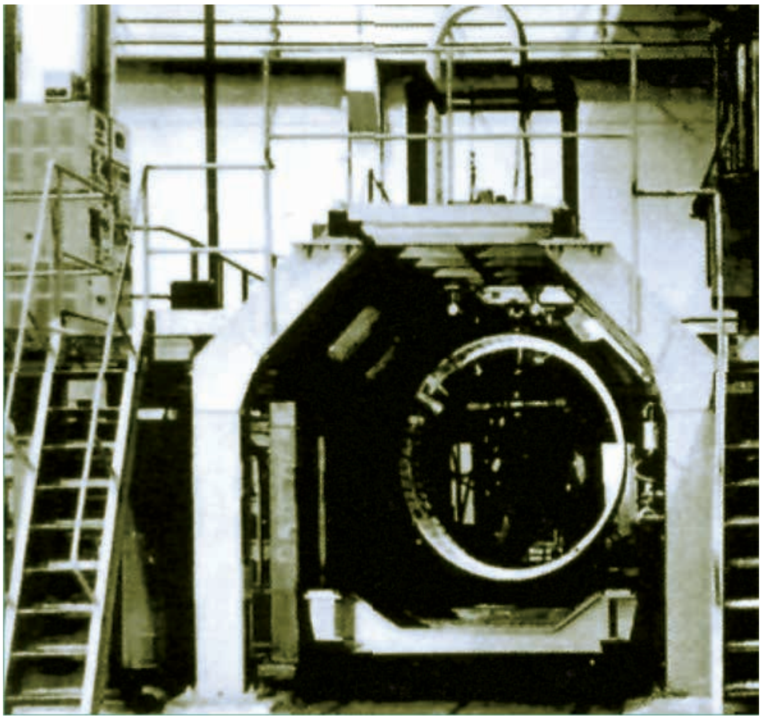
EBW of fuel tanks from high-strength Al-alloys of Al–Cu, Al–Mg–Mn, Al–Mg–Li systems up to 42 mm thick, and welding of cut-in flanges into cylindrical shells provides welded joint strength not lower than 0.8 of base metal strength, minimum welding deformations and high tightness of welds, i.e. it allows lowering structure weight and increasing its geometrical accuracy. The main characteristic of machines designed for these operations, is integration in the welding position of tools for machining the edges directly before welding. This is exactly the way to provide the required small gap (usually less than 0.1–0.15 mm) in the butt of edges to be welded and minimize the time between edge machining and start of welding.



Location of EBW longitudinal welds on «Energy» carrier rocket fuel tanks with outer diameter of 7.8 m



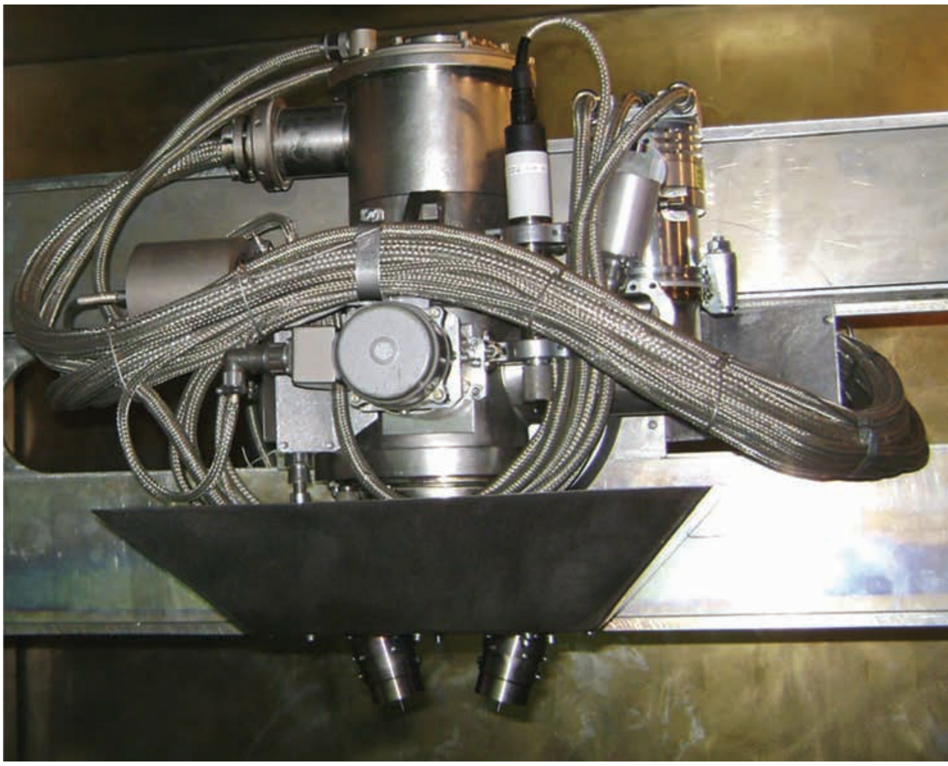
General view of the machine for EBW of longitudinal welds of shells with preliminary machining of edges and post-weld X-Ray quality control of welded joints



Machine for EBW of cut-in elements into shells with local evacuation of weld zone. The machine has two working positions: for hole machining and for welding

It should be specially noted that a distinctive feature of the units designed by PWI for EBW of bulky workpieces, is application of in-chamber electron guns, moving in the range of up to 12 m.

This solution allows maximum increase of the coefficient of uutilization of vacuum chamber internal volume. To prevent substantial deformation of vacuum chamber walls at its evacuation, and of the guides fastened on them, along which the welding gun moves, the chamber is made to have two vacuum-tight relatively thin-wall shells (each 8–12 mm thick), connected to each other by stiffeners — frames.



General view of 60 kV, 60 kW welding gun module moving inside the vacuum chamber

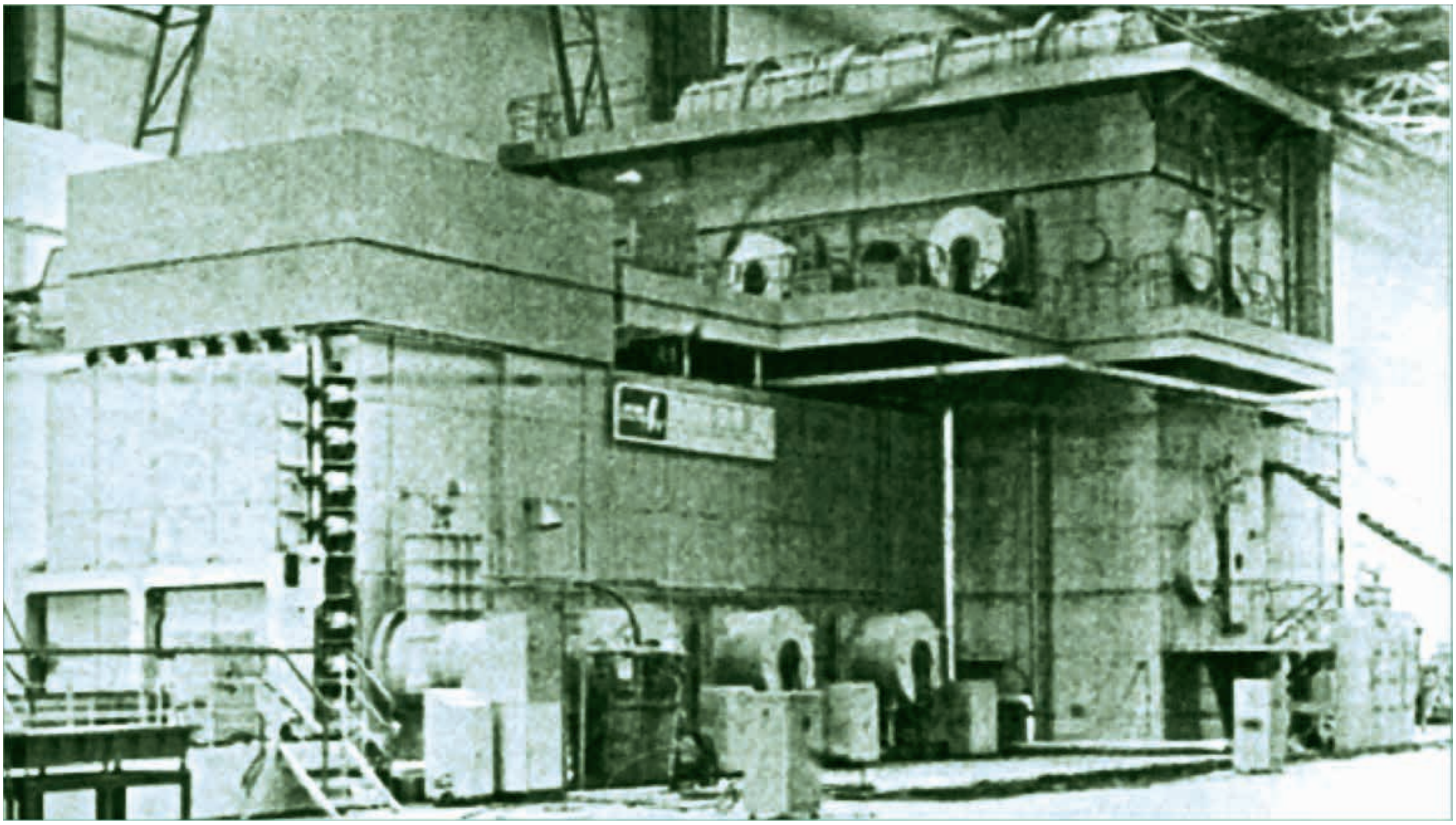
KL-109 unit with box-shaped walls

Application of such box-shaped design of walls and doors (KL-109 unit) instead of regular T-shaped design permits achieving two times higher moment of inertia and, as a result, lower wall deflection at chamber evacuation. In addition, elimination of outer stiffeners allowed improving chamber appearance and eliminating dust accumulators on its outer walls, which is of great importance for workshops.

Specialized machines KL-134 with welding gun sliding on the chamber upper cover and KL-154 machine were developed for electron beam welding of titanium spherical tanks for space application.

EBW in aircraft construction

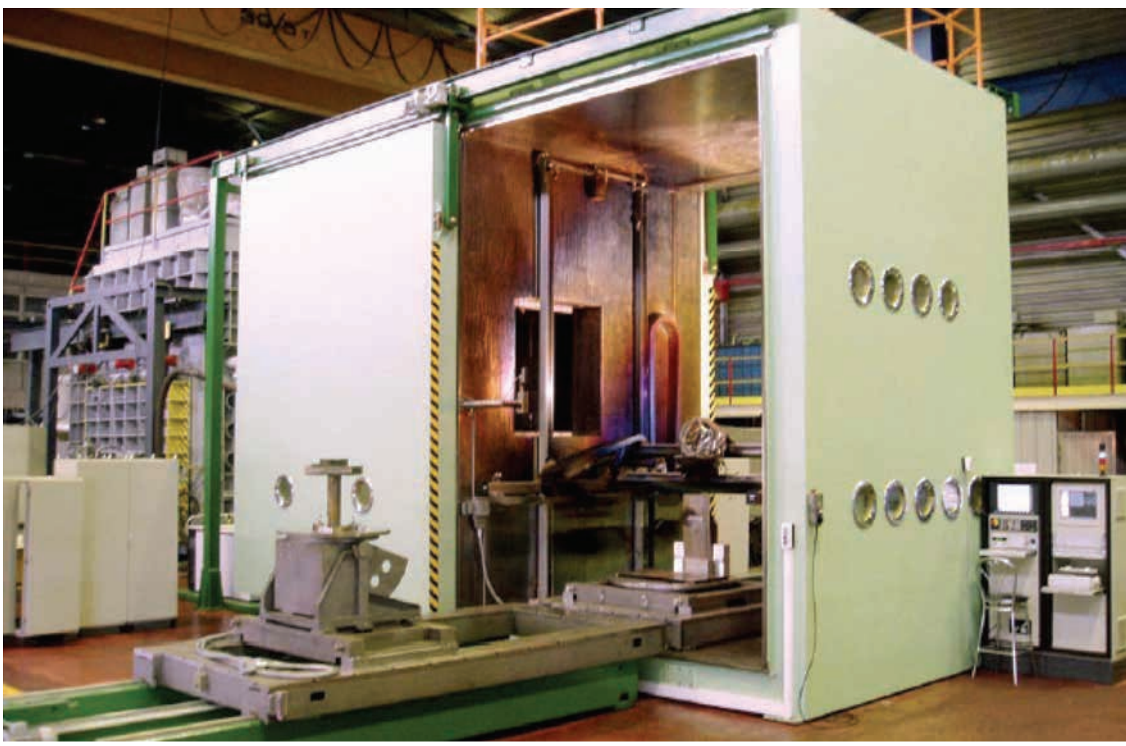
The first experience of electron beam welding application in manufacturing of aircraft frame structures was gained in 1985, when the aircraft industry developed ELU-24×16 machine with PWI involvement for welding titanium alloy center wing at S.P. Gorbunov Kazan Aircraft Factory.



Vacuum chamber of this machine consists of the main tower and tunnel parts abutted to it from opposite ends. The tower and each of the tunnel parts have the following inner dimensions: length × width × height are equal to 4×10×12 and 17×4×4 m, respectively. Thus, the total length of the chamber is 38 m and the total volume of vacuum chamber is 1160 m^3. The machine is equipped with loading table with rotator, having a vertical axis of rotation. The welding gun inside the chamber is mounted on the manipulator in the main tower and moves along its height (travel of 3.3 m) and in the transverse direction (travel of 4 m). Power unit of the machine designed by PWI, contains automatic seam-tracking system; maximum beam power is 120 kW at accelerating voltage of 120 kV.

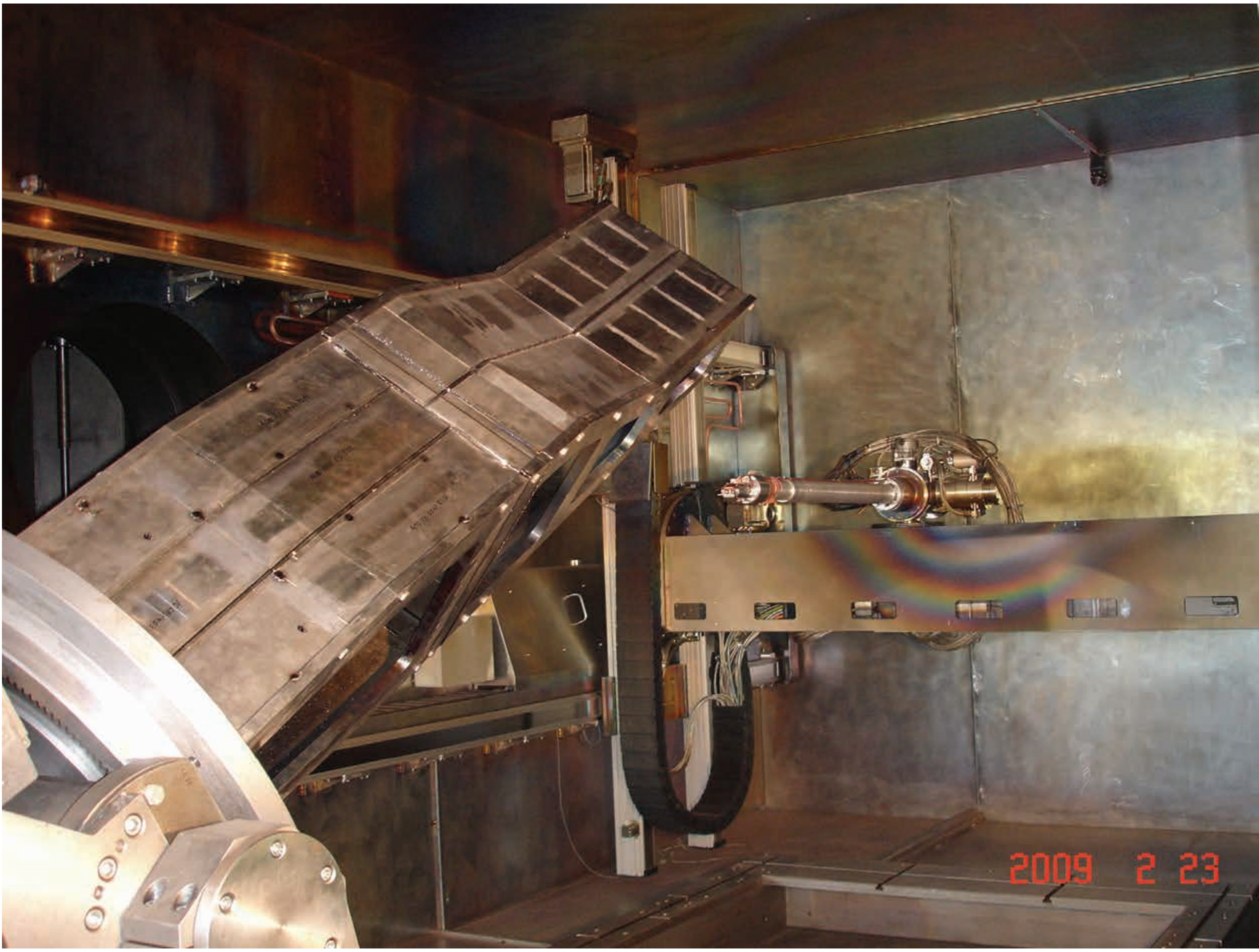
KL-115 machine and welded component of a jet engine

KL-115 and KL-118 machines were developed for application in the US aircraft industry



KL-118 machine

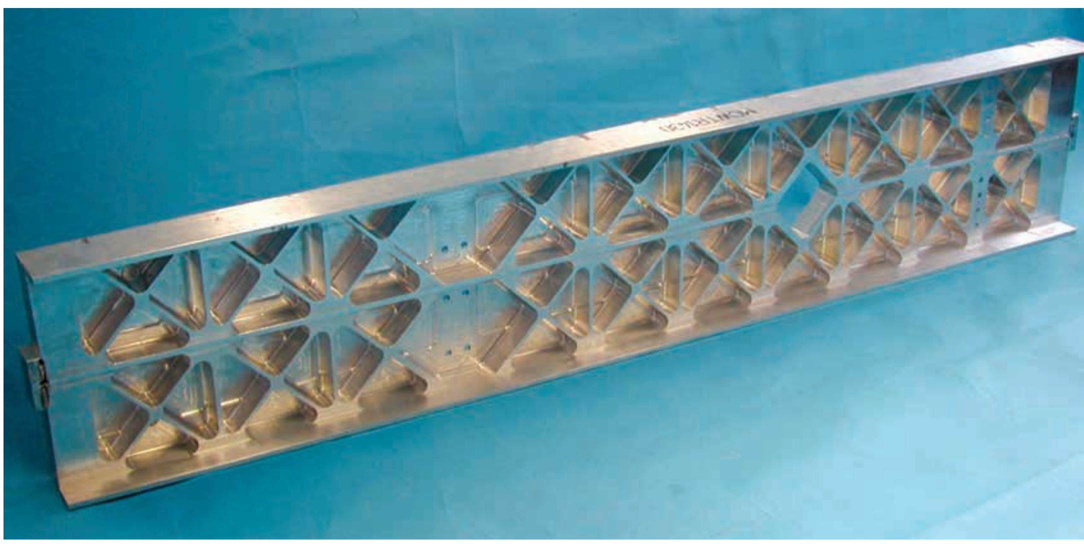
In 2009 in order to manufacture a welded beam for a titanium pylon of the Russian civil aircraft Sukhoi Superjet 100, KL-138 machine was developed and put into operation at Joint Stock Company «Komsomolsk-on-Amur Aircraft Production Association» named after Yuriy Gagarin.



A distinctive feature of this machine is availability of devices for cosmetic smoothing of weld roots, including the difficult-of-access remote areas. For this purpose an electron beam is turned through 90^{o} and the accuracy of beam alignment with the butt joint is controlled by the RASTR system. KL-144 machine equipped with a two-section vacuum chamber of 100 m^3 volume has also been put into operation in the same Association.

КL-132 machine was developed for EBW of jet engine components of SU-30 fighter at HAL Company plant (Koraput, India)

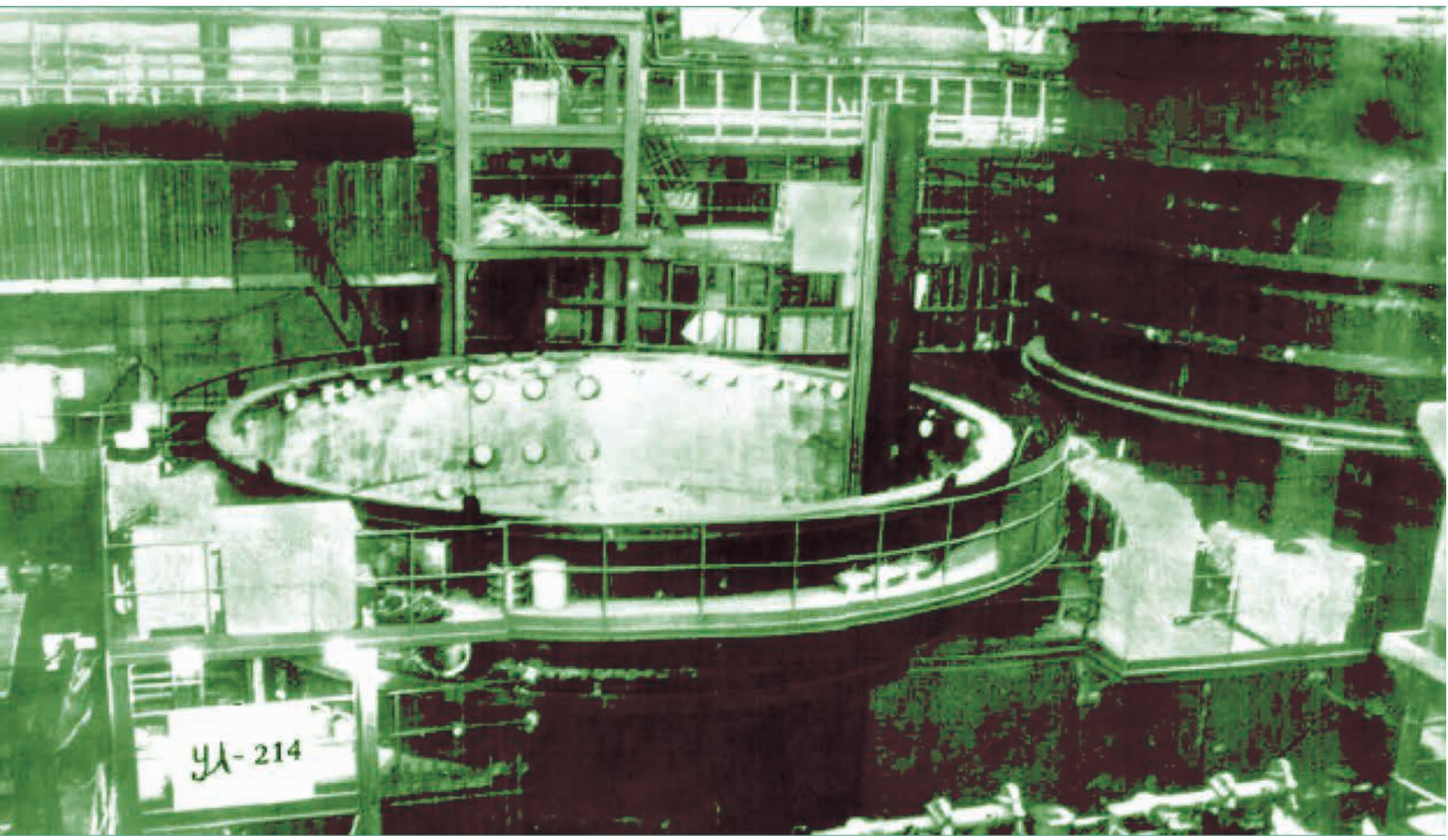
In order to solve another task of the aircraft industry – development of welded wings – PWI performed a large scope of work on welding large-sized panels from high-strength aluminium alloys.

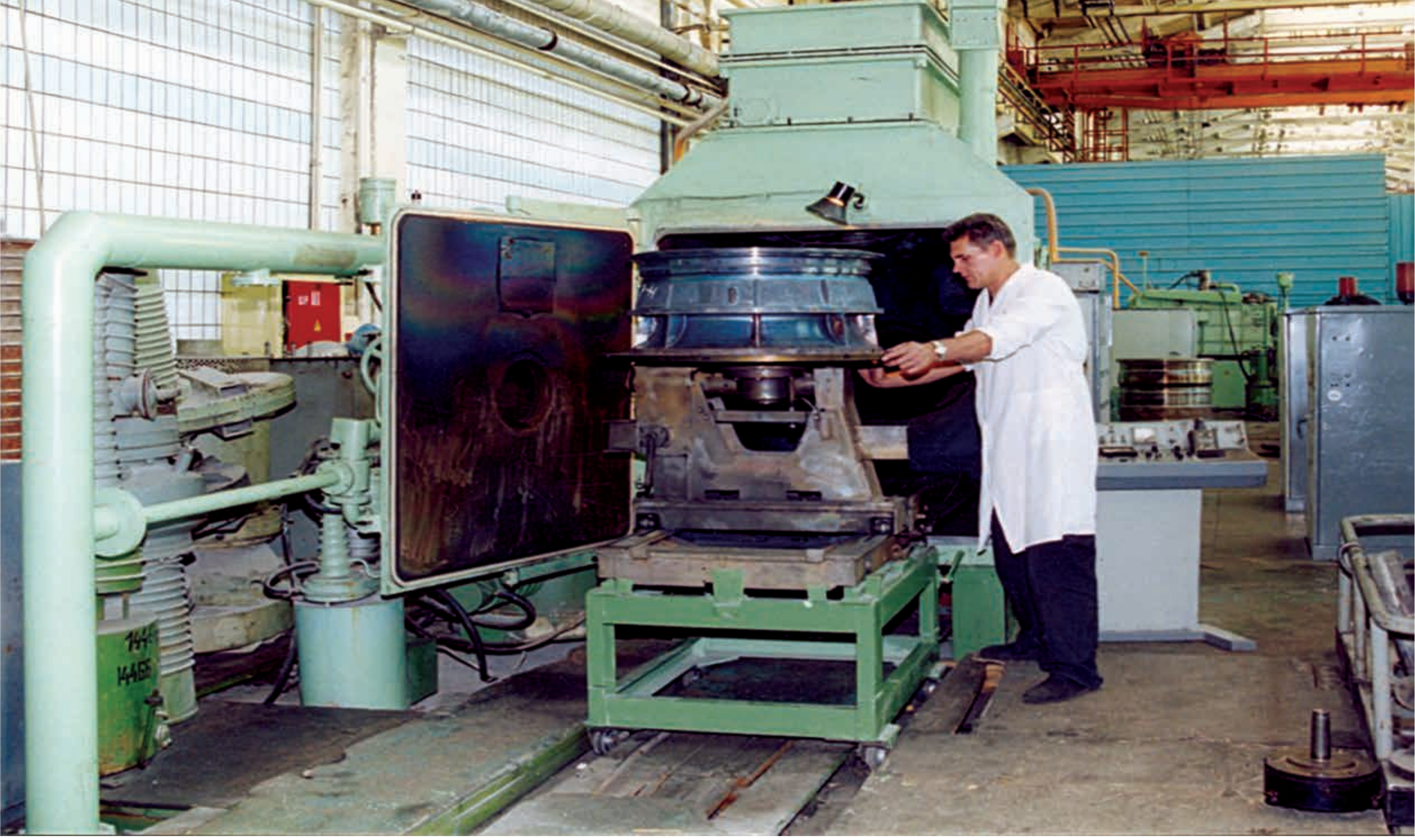


EB welded beam of a wing made of high strength aluminium alloy 100 mm thick

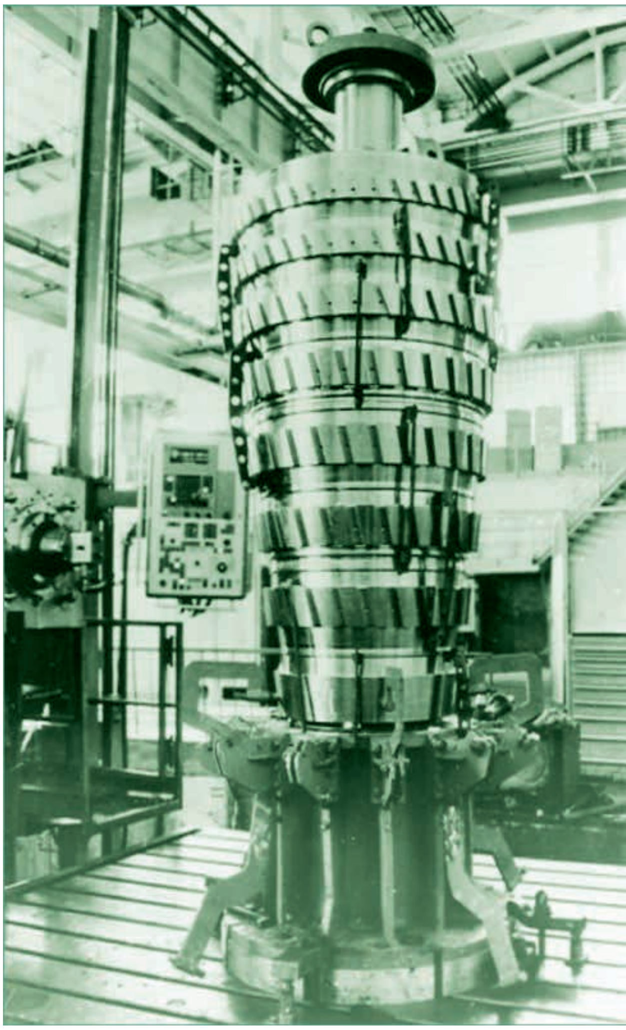
EBW in shipbuilding industry

In 1980-s UL-214 machine was developed for single-pass welding of longitudinal and girth welds on large-sized marine structures of up to 8 m diameter from titanium alloys with wall thickness of 100 mm and more. This machine is successfully used now at Production Association «Severnoje Mashinostroitelnoje Predpriyatie» (Severodvinsk, Arkhangelsk region, Russia). Power of its power unit is 60 kW at accelerating voltage of 60 kV. Inner dimensions of the vacuum chamber are as follows: diameter — 10.4 m, height — 9.6 m; volume — 860 m^3. Diameter of the faceplate with vertical axis of rotation is 7 m, permissible load is 150 tons. Operating vacuum in the chamber is $6.5 \cdot 10^{-3}$ mm Hg. Experience of UL-214 machine operation demonstrated the possibility of successful welding of titanium alloy PT-3V of 100– 200 mm thickness with up to 1.0–1.5 mm gaps in the butt joint, edge misalignment of up to 15 mm, edge opening from the face and back of the weld of up to 1.5–1.7 mm.



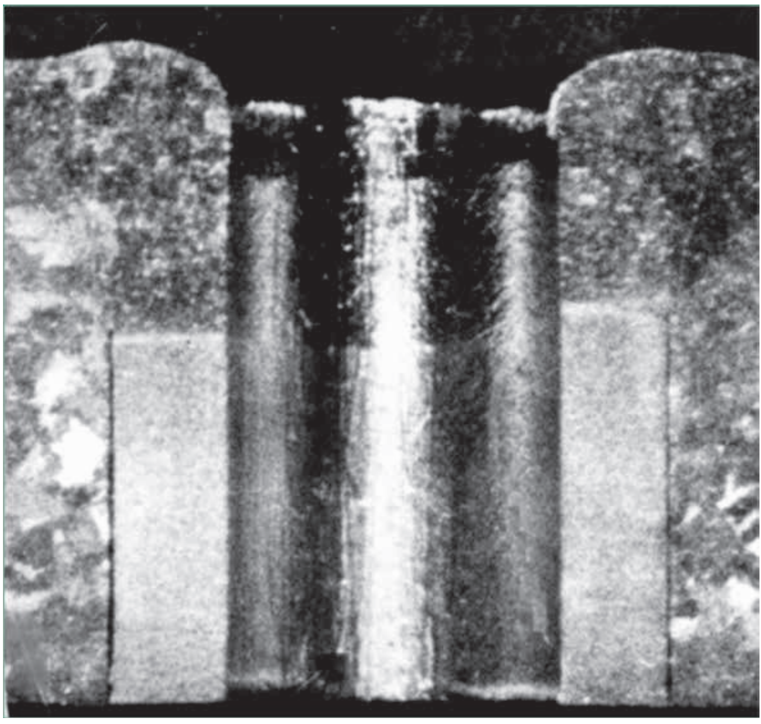


With PWI involvement extensive application of electron beam welding in manufacturing of ship gas turbine engine-power units was mastered at production complex «Zorya»-«Mashproekt» (Nikolayev, Ukraine). The same units are used as blowers for main gas pipelines. Welds are performed in 80 components and parts of one such engine by electron beam welding.



For a similar purpose in 1984–1986 a machine was put into operation and a series of investigations on electron beam welding of rotors of gas-compressor units with the capacity of 25 MW were carried out at Nevskiy factory (St-Petersburg, Russia)

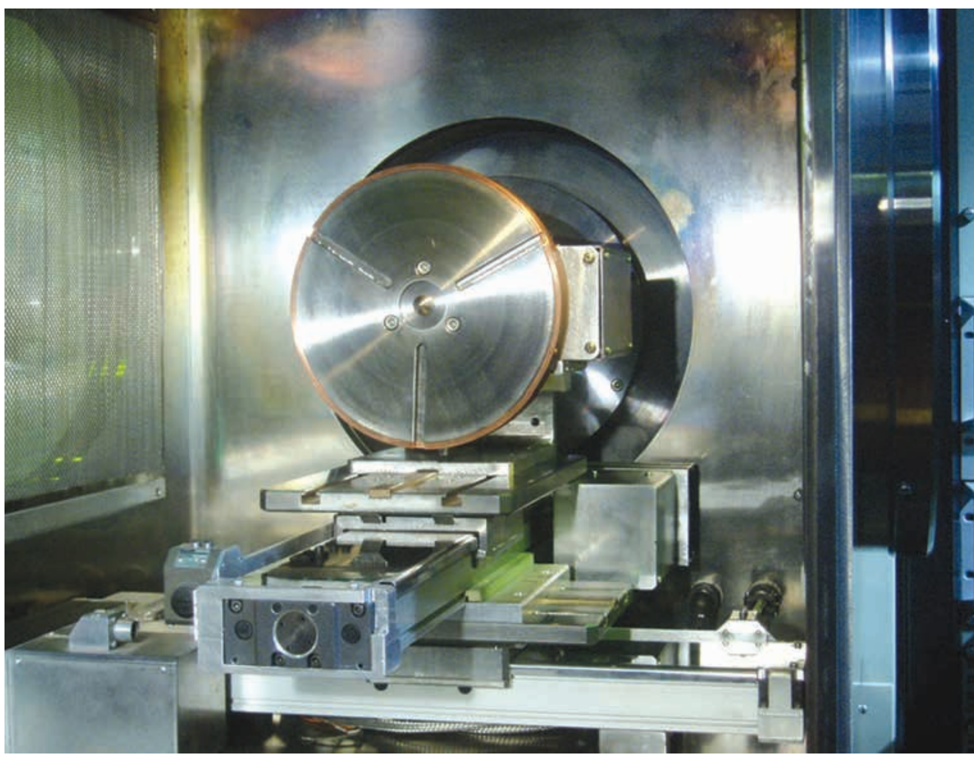
A number of specialized machines, including UL-178M machine (Afrikantov EDBM, Nizhniy Novgorod, Russia) were developed for welding tubes to tubesheets of heat exchangers of ship engines. Transverse macro-section of welded joint 6.5 mm deep confirms the high quality of welding.



Small-sized machines for EBW in instrument-making industry

Ten SV-112/103 machines with vacuum chamber inner dimensions of $640 \times 640 \times 640$ mm were put into industrial operation for EBW of small items. Time of evacuation to the vacuum of $5 \cdot 10^{-4}$ mm Hg is less than 5 min.

SV-112 machine is equipped with a stationary gun of up to 15 kW power and two-coordinate table (X–X' and Y–Y', 200 mm travelling distance), universal rotator, and back centre.



High-performance machines
for EBW of gears and drilling bits

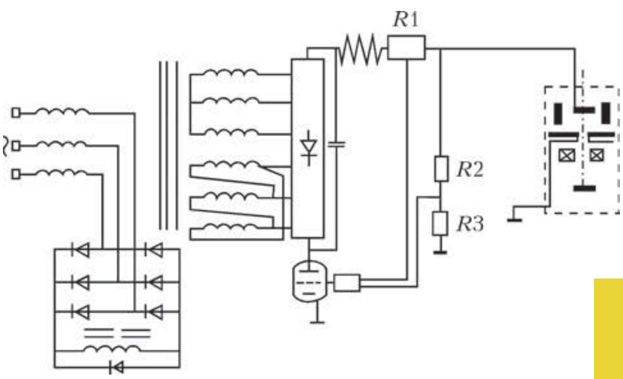
Commercial machines of the so-called stroking type (UL-157, AVTO-ZAZ, Melitopol, Ukraine) are used, in particular, for welding of gear box clusters.

Specialized machines for simultaneous performance of three longitudinal welds on drilling bit bodies also belong to this class of units.

High-efficient 3-gun machine KL-117 is applied for EBW of drilling bits of various typesizes. Two machines are operated by «Volgaburmash» Association (Samara, Russia) and one machine — by «Smith Tools» Company, Ponka City, USA.

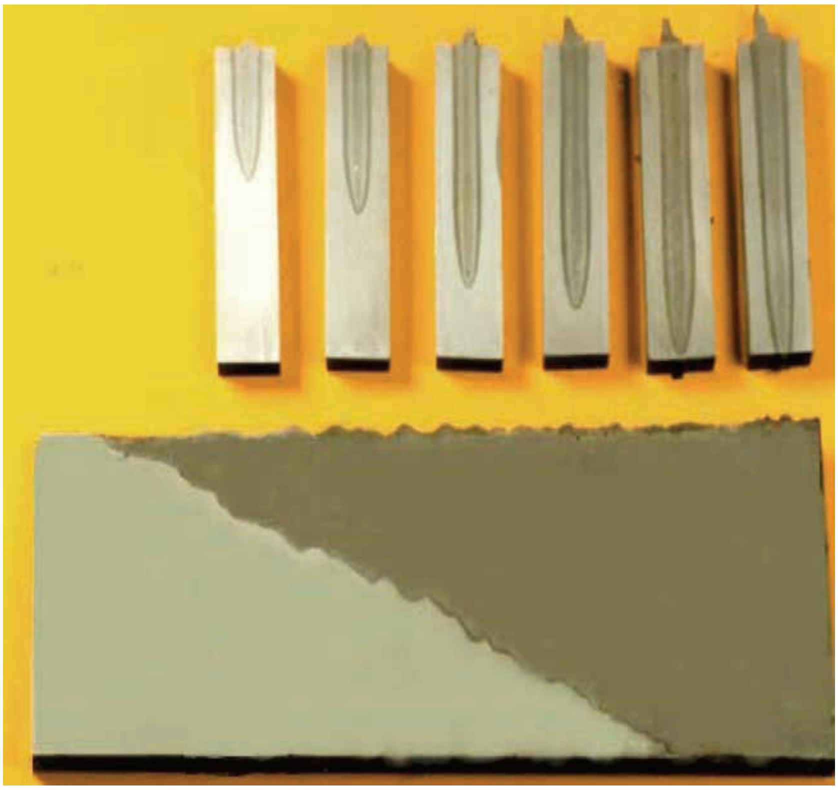
ELECTRON BEAM WELDING GUNS AND POWER SOURCES

Development and manufacturing of power units – guns, their power sources and computer control systems is a priority area of PWI activity. Vacuum tube PP-2 was used as the linear transit element in up to 120 kW source and this solution remains effective up to now. Already in early abnormal transient process in the welding gun emission system — at increase of specified beam current by 5–10 % — the vacuum tube catches the accelerating voltage for the time of about 5 ms. In a few milliseconds, when the dielectric strength of the emission system is fully restored, accelerating voltage in the gun is also restored and the welding process proceeds without any disturbance of weld formation quality.



Simplified block diagram of high-voltage power source ELA-60 fitted with electron tube PP-2

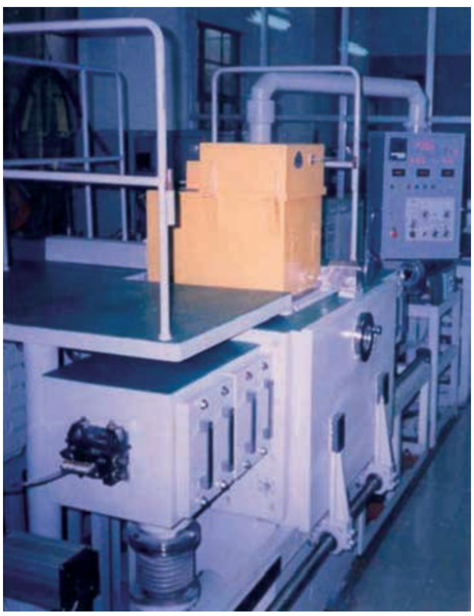
High stability of accelerating voltage maintenance and suppression of electric breakdowns permitted achieving defect-free, «spiking-free» weld formation in the area of girth weld on thick-walled structures.



Transverse (above) and longitudinal (below) macrosections of the cast zone on heat-resistant steel 130 mm thick in the critical region of girth weld closure

The desire to reduce the stored energy in the accelerating voltage source for the purpose of breakdown suppression in the welding gun, reduction of overall dimensions and weight of the power source led to development of inverter power sources at PWI. Application of inverter power source in electron beam welding of continuous belt blanks, including those made of such dissimilar metals, as tool + carbon steels, turned out to be rather effective. Ten complete sets of 120 kV 6 kW power units with computer control were developed and put into commercial operation for the appropriate machines.

General view of both power source ELASM-120/6 and welding gun

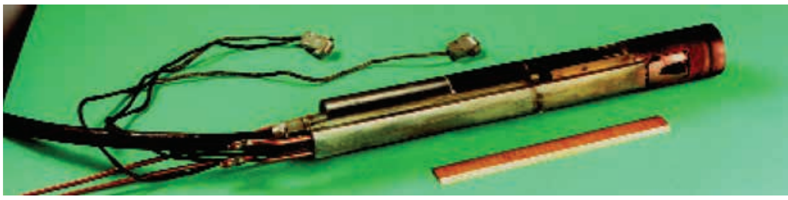


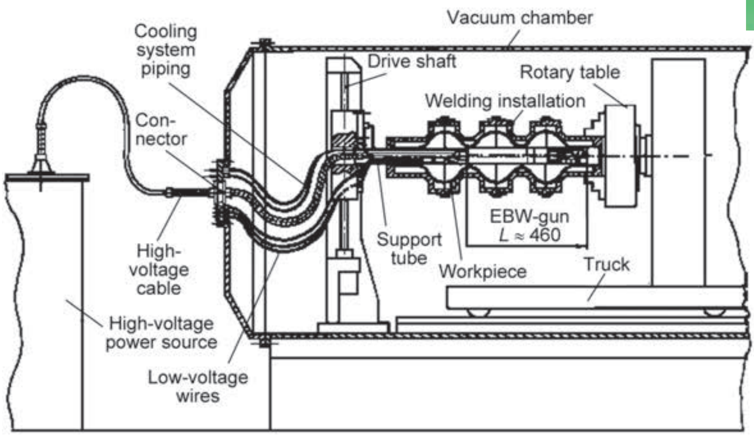
General view of one of the production lines, manufactured by the joint venture and operating in China

Transverse macrostructure of welded joint of R6M5 + 50KhFA steels 1.35 mm thick, welding speed of 7.8 m/min, accelerating voltage of 120 kV, beam current of 12.5 mA, width of cast zone in weld upper part and weld root is 0.35 and 0.25 mm, respectively

By 2010 positive results of application of inverter power sources of 60 kW power had been obtained, but in their operation in the beam current pulse modulation mode the accelerating voltage stability is still disturbed. Weld formation is also disturbed, accordingly, and operation of the real time seam tracking system is made more difficult. In particular, it was not possible to use the inverter power sources for EBW of high-frequency cavities from niobium alloys.

Transient processes in the accelerating voltage power source at beam current pulse modulation cause an abrupt change in beam position relative to the butt of edges being welded, as the beam is rotated through 90° by the electromagnetic system, which is extremely sensitive to accelerating voltage magnitude. To solve this problem PWI developed equipment with application of power source with a flashless electron tube.





General view of the gun and schematic of a machine for in-pipe EBW of high-frequency Nb-alloy cavity with smooth surface of the weld inside the cavity (development was made for Mitsubishi Heavy Industries, Japan)

In 2008 LN LASER Company (Daejeon, South Korea) put into operation a machine with 6×6×6 m vacuum chamber, equipped with PWI 120 kV, 120 kW power unit and gun moving inside the chamber

This is an example of effective application of EBW of a component of reactor case made of 100 mm thick aluminium alloy and applied for manufacturing large-sized liquid-crystal screens.

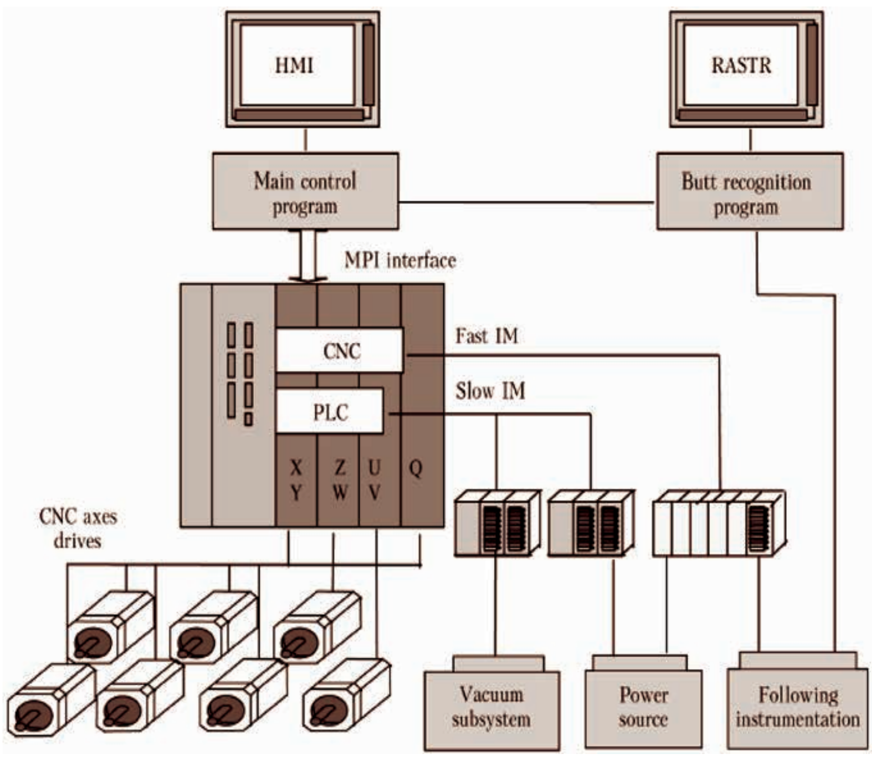
Main characteristics of PWI commercial power units as of mid-2010

Parameters	Switch — mode type					Control tube is applied		
	ELASM-60/1.2	ELASM-60/6	ELASM-60/60	ELASM-120/6	ELASM-120/18	ELA-60/30	ELA-60/60	ELA-120/120
Beam power, kW	1.2	6	60	6	18	30	60	120
Accelerating voltage, kV	60	60	60	120	120	60	60	120
Range of welding current, mA	0.1–20	0.1–100	0.1–1000	0.1–50	0.1–150	0.1–500	0.1–1000	0.1–1000
Stability of voltage and current, %	±0. 5							
Angle of beam deflection, deg	±3.5							
Distance from gun to workpiece, mm	100–300							
Cooling water:								
• pressure, MPa	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
• flow rate, l/min	5	5	25	5	5	25	25	35
Weight, kg:								
• gun	55	55	55	60	60	55	55	60
• gun radiation protection	130	–	–	130	130	–	–	130
• power source	185	460	1300	735	735	3750	4000	6000
Computer control and RASTR system	Yes							
Mains 50/60Hz, 30/220 ±10 %, kVA	1.5	7	70	7	20	35	70	135
Maximum penetration depth, mm:								
• steel	3	12	100	15	60	75	100	250
• titanium alloys	3.5	15	150	20	100	110	150	400
• aluminium alloys	5	30	200	35	140	150	200	450

COMPUTER CONTROL OF EBW WITH MULTI-COORDINATE MOVEMENT SYSTEM

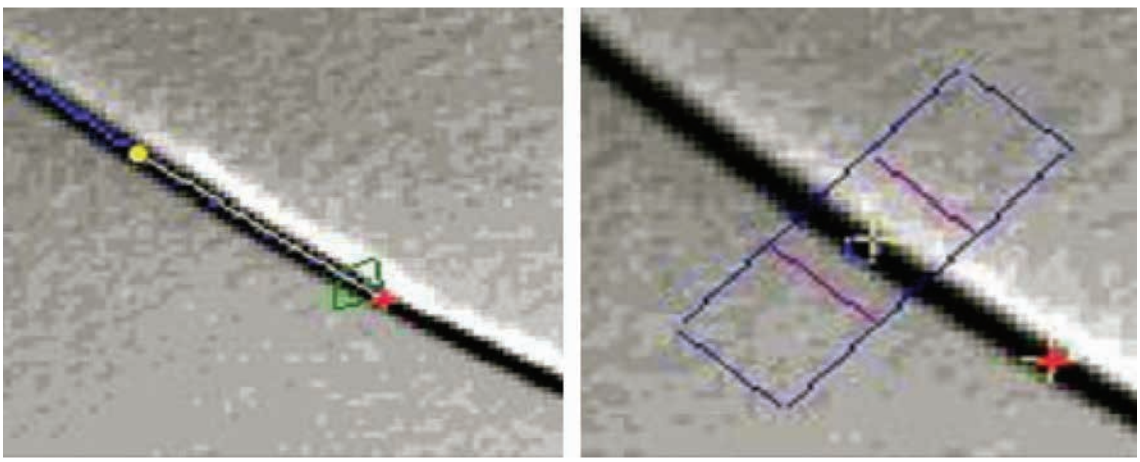
Staying focused on application of highly accurate industrial CNC-systems, at the end of 1990-s, PWI, in co-operation with the Institute of Problems of Mathematical Machines and Systems of the NAS of Ukraine, developed software tools, allowing an operator to use the so-called visual method for designing EBW programs for complex constructions. In addition to traditionally used computer system, which is a combination of CNC and PLC, the following is introduced:

- higher level of HMI (Human machine interface) — an operator's interface for visual design of operating programs and control of the welding process;
- an additional computer, which independently of other processor nodes, solves the problems of butt joint recognition by workpiece surface image received from RASTR tracking equipment, and jointly with HMI computer, provides the functions of automatic teaching, correction and tracking the butt joint.



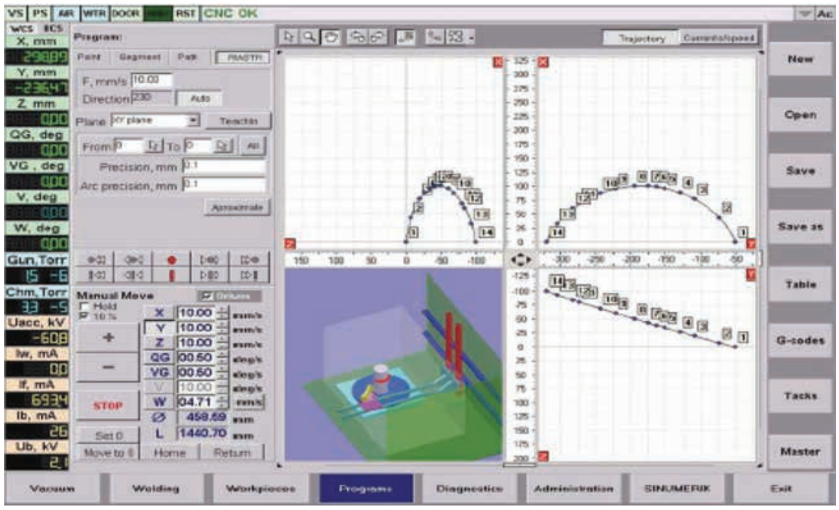
Hardware architecture of computer control system

The principle of operation of RASTR tracking equipment is based on measurement of current of secondary emission electrons, formed at cyclic scanning (with 300 mc period) of the workpiece working area by sharply focused low power beam in short-term periods (up to 5 mc) of welding process interruption. Workpiece surface image is formed by signals from secondary emission electron pickup, placed on the electron gun in immediate vicinity to the welding area. Determined and numbered by the tracking equipment, brightness levels of scanned surface sections are stored by the computer as an image frame (matrix) and reproduced in a separate window of RASTR monitor after special software processing. In order to write the welding program of spatially complex weld, a procedure of automatic teaching is also envisaged, which uses the image of butt joint of edges to be welded.



View of a window with the image of workpiece surface on RASTR monitor at automatic training (left) and at butt following (right)
(cross shows the location of an electron beam on the workpiece)

Trajectory formed during automatic teaching, is represented in the basis coordinate planes.



View of HMI monitor screen in the mode of visual design of EB welding program for the case of performance of an inclined semi-circumferential weld on a cylindrical body by four-coordinate displacement of the gun, namely rotation and displacement by three linear axes

In 2010 eighty employees, working on an area of 3000 m^2, are directly and exclusively engaged in electron beam welding at PWI. The scope of completed tasks is as follows: investigations of welding technology:

- designing of mechanical and electrical sections of machines;
- development of electron guns, power sources and control systems;
- assembly and testing of complete machines and power units;
- putting of the produced machines into commercial operation;

Since the «Sumy Factory of Electronc Microscopes» stopped producing the equipment, PWI have undertaken the manufacturing of power units, including welding guns, their power sources and computer control systems.

For the last 10 years, 56 complete sets of diverse EBW equipment, including machines with up to 100 m^3 volume of vacuum chambers, have been put into commercial operation and are being manufactured now.

Electron beam deflected through 90º is applied for welding difficult-of-access zones