WELDING FABRICATION IN GAS TURBINE CONSTRUCTION (Review)*

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The paper deals with modern developments of gas turbine units and commercial application of advanced welding and related technologies: electron beam welding, laser cutting, vacuum brazing, surfacing, etc.

Keywords: *welding technology, gas-turbine units, new materials, arc welding, laser cutting, electron beam welding, electroslag welding, plasma-powder surfacing, vacuum brazing*

Southern Turbine Plant (now called State Enterprise «Zorya»–«Mashproekt») was established at the start of 1950s with the purpose of development and batch production of gas turbine equipment for warships of the USSR Navy. At the start of 1979 the Enterprise mastered batch-production of gas turbines for pumping natural gas and producing power in mobile and stationary power plants.

«Zorya»–«Mashproekt» accumulated tremendous experience of development of various-purpose gas turbine units (GTU), namely for the drive of natural gas compressors, power engineering and navy power plants.

During more than fifty years of Enterprise operation, the design bureau developed 56 types and modifications of gas turbine engines (GTE), 38 types of different reduction gears, which were the basis for development of more than 70 types of GTU, which have been adopted and still are operated by the navy of CIS and a number of other foreign countries. More than 1700 navy GTE have been manufactured, which were used to equip more than 65 % of waterborne ships of USSR Navy by the start of 1990s. Total power of engines mounted on the ships is up to 17 mln hp, and their operation time is equal to 3 mln h.

At present more than 800 GTU produced by «Zorya»–«Mashproekt» are in operation at compressor stations, their total operation time being equal to 75 mln h. The Enterprise continues operating actively towards improvement of the currently available and development of promising GTU for gas-pumping units. Development of a regenerative cycle GTU of the rated power of 16 MW with more than 40 % efficiency for gas-pumping unit drive became one of the promising projects.

«Zorya»–«Mashproekt» is actively pursuing development of industrial type GTE for power engineering. The design features of such engines are two-support rotor design, absence of gas-dynamically isolated (free) generator turbine, high (up to 500–550 °C) gas temperature at the engine outlet, ability to maintain it in the partial regulation mode due to adjustment of air flow rate at engine inlet.

«Zorya»–«Mashproekt» developed industrial-type power GTU GTE-110 of nominal power of 110 MW with 36 % efficiency. This unit was the basis for development of projects of steam-gas plants (SGP) of the nominal power of 160 and 325 MW, with the efficiency of 50.2 and 51.5 %, respectively.

Samples of power units GTE-45(60) and UGT5000 of the nominal power of 60 and 5 MW, respectively, were made. GTE-45(60) unit is designed for use in «large-scale» power generation as part of GTU, and UGT5000 — as part of cogeneration units.

Compared to earlier developed units, UGT5000 has a number of fundamental differences. Therefore, designers, technologists and manufacturers are now solving the issues they have never faced before.

Different materials are used for manufacture of modern GTE (Figure 1), namely low- and high-alloyed (high temperature-resistant and high-strength) steels, titanium alloys, nickel wrought and cast dispersion-hardening alloys. Application of high-alloyed heat-resistant and high-temperature alloys, as well as wide use of welding and related technologies in engine manufacture, ensured high GTE performance at minimum weight and dimensions characteristics.

«Zorya»–«Mashproekt» has mastered modern technologies of laser cutting, electron beam welding (EBW) and electroslag welding (ESW), surfacing, vacuum brazing and other processes.

Laser cutting of sheet (up to 12 mm) material is performed by «Baystar-3015-3» laser system of «Baystronic» company, which consists of CO_2 laser with 3 kW output power with high-frequency pumping, gantry with high-speed drives, two replaceable working tables for sheets of 1.5 × 3.0 m size, computer unit for control of the process of cutting and monitoring the working mixture composition, gas bottle block for working mixture preparation, laser cooling unit with automatic maintenance of the set temperature, unit for aerosol suction from the cutting zone and feeding

*Published by the materials of the paper presented at scientific-technical conference held at the Admiral S.O. Makarov National Shipbuilding University on October 14–17, 2009.

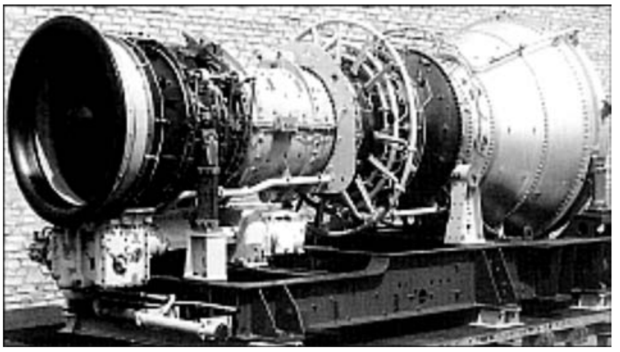


Figure 1. GTE DN-80 appearance

cleaned air back to the premises, unit for sheet loading and removal of cut out parts; it also incorporates a unit for cutting out shaped holes on pipes of up to 200 mm diameter.

Highest grade gases are used for laser radiation generation, namely commercial nitrogen, carbon dioxide gas and helium, and oxygen is used as cutting gas.

At present, the range of cut out parts includes many thousand part names. Parts cut out by the laser do not require and further machining.

EBW became the most widely accepted in fabrication of stator and rotor components. This is due primarily to the fact that this welding process combines a highly concentrated heat source and the most perfect means for molten metal protection, namely vacuum. The above EBW features allow welding alloyed, austenitic and martensitic steels, nickel and titanium alloys up to 100 mm thick with minimum deformations without edge preparation or filler wire application.

EBW sections were set up in the test and batch production facilities of «Zorya»–«Mashproekt» in cooperation with PWI. Vacuum chambers and displacement mechanisms were developed and manufactured by the enterprise staff. U-250A, ELA-15, ELA-30, ELA-60/60, ELA-60 power units are used for electron beam generation. A dimension-type series of the units has been developed, allowing welding stator components from blade units to large-sized components of 3.5 m diameter, as well as rotor shafts and drums.

Figure 2. Macrosection of EB-welded overlap joint of flue tube shells

Section of batch production is fitted with «Protok-10» device for demagnetizing the components before welding and with the required instrumentation. The above sections are located in immediate vicinity of each other, allowing quickly solving the arising problems.

At present EBW is used to perform about 70 % of welding operations on GTE components, and manufacturing of these engines is already unthinkable without it. This allowed gas turbine designers developing and introducing into batch production a number of fundamentally new welded structures, namely low- (LP) and high- (HP) pressures compressor rotors, central drive gears, HPC shafts from materials VT31, VT8, VT9, EP 609, EP 517.

Application of new materials (EP 609Sh, EP 866, EP 517) for manufacturing thick-walled components required a fundamental retrofitting of EBW techniques. Work has been performed in cooperation with PWI on development, mastering and introduction of beam control systems (SU-65, SU-29, SU-259). A new technology has been introduced, namely EBW with a horizontally located gun with electron beam rotation by a preset prgoram. All this allowed solving the problem of welding components with up to 70 mm wall thickness.

Flue tubes from EI 602 alloy of second generation engines (wall thickness $\delta = 2.5$ mm) and from VZh 98 alloy of third generation engines ($\delta = 1.5$ mm) are some of the most highly stressed elements, as they operate under the conditions of the impact of high thermal and vibration loads and determine the service life of the flue component. Attempts at making the joints using argon-arc welding (AAW) failed, as the weld root developed a brittle film, promoting initiation of longitudinal cracks. Investigations of overlap joints of thin-walled shells made by EBW, confirmed the effectiveness of this technology. A process of EBW of flue tubes with application of electron beam scanning by a specially designed generator was developed. Selection of amplitude, frequency and relative oscillation duration of the electron beam, allowed achieving a uniform penetration in the overlap joint of flue tube shells of up to 8 mm width (Figure 2). Figure 3 is the appearance of the flue tube, made with EBW application.

The fusion line metal structure does not have any oxide films or other defects. Transverse macrosections of the weld show that at EBW the length of the HAZ is equal to 1.5–2.5 mm, whereas at AAW it is equal to 10–12 mm. Width of the zone of heat contact of overlap joints increased 2–3 times. Flue tube EBW allowed item service life to be extended 4–6 times.

GTE nozzle vanes are particularly heavy-duty items, and are exposed to thermal and dynamic loads, bending moment and torque, as well as salt and sulfide

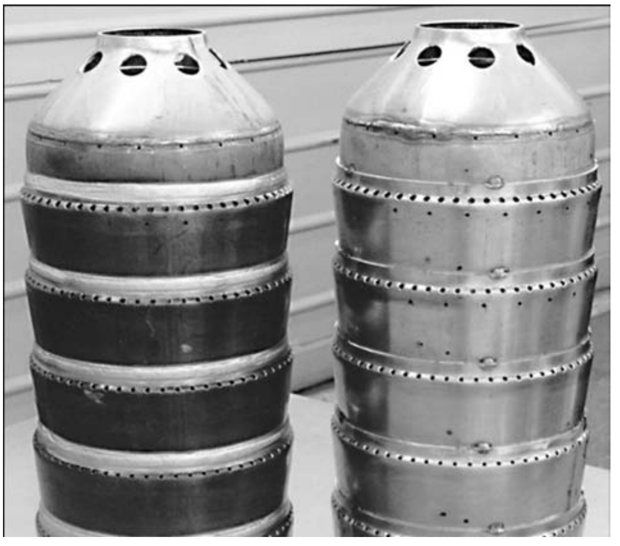


Figure 3. Appearance of flue tube (EI 602 alloy, δ = 2.5 mm) with five circumferential EB welds

corrosion; they are also exposed to erosion wear. It did not seem possible to produce sound joints of EP 539LM, ChS 70L, EK 9L, ChS 104 alloys applied for nozzle vanes of navy gas turbines, using arc welding processes, in view of the low technological strength of these alloys.

Proceeding from the results of experimental investigations, the ways of improvement of technological strength and main conditions of producing sound welds of vane units of nozzle blocks from EP 539LM, EK 9L alloys and other materials by EBW in forced modes with application of electron beam modulation were determined (Figure 4). Engine tests showed the high reliability of welded joints of nozzle block vane units.

Rotors of LP- and HP-compressors with speeds of 2000 rpm at high pressure are particularly critical compressor components. Rotor welded structure without closed cavities in the axial direction, in which the discs are connected not by pins, but by EBW, is more reliable in operation and adaptable to fabrication. As the discs come up for welding with finished slots, the difficulty of rotor fabrication consists in producing after welding the minimum radial and face runout of the component, not greater than 0.3 mm.

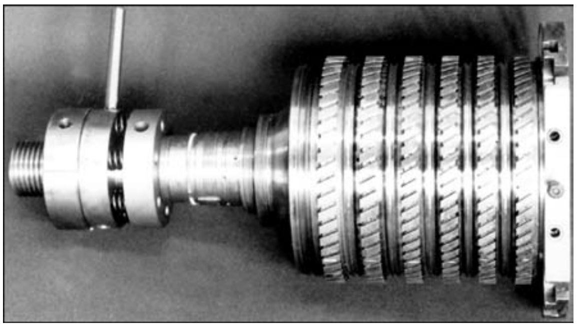


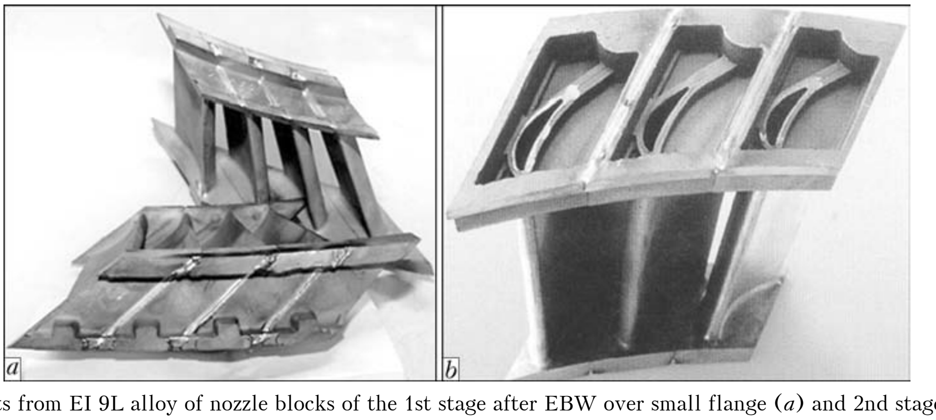
Figure 5. Appearance of all-welded HPC rotor from VT31 titanium alloy

In order to obtain a component of required dimensions, welding and subsequent heat fixation of rotors are performed in specially developed fixtures, which rigidly fasten each disc by its inner body diameter. Disc joining is performed on an aligning substrate 5–8 mm thick. After welding the component is heat-treated to relieve internal stresses and improve ductility properties of welded joints, and the substrate is cut off to remove defects in the weld root.

Manufacturing all-welded rotors of gas turbines from VT31, VT8, VT9 titanium alloys and EP 609, EP 517 alloys by EBW (Figure 5) is a considerable achievement of welding engineering. Tests of welded rotors conducted in rigs and engines showed their high performance.

Manufacturing of some GTE components requires materials, combining high strength and ductility, high temperature strength and heat resistance, hot hardness and thermal stability under operation conditions close to the limit ones. It is impossible to combine all these requirements in one material. Therefore, products are developed, the individual parts of which consist of various materials, the most suitable for operation conditions. Such dissimilar materials can be combined in one item using technologies of vacuum brazing or brazing in argon flow.

«Zorya»–«Mashproekt» has mastered the technology of vacuum brazing of air-cleaning and fuel filters, connector blocks, honeycomb and metal-ceramic seals, guide vane units, cages, igniter cases, torch device fittings, etc. Excellent results were obtained in repair of defects in castings from high-temperature nickel



a

b

Figure 4. Vane units from EI 9L alloy of nozzle blocks of the 1st stage after EBW over small flange (*a*) and 2nd stage after EBW over large flange (*b*)

Figure 6. Appearance of brazed parts and products: *a* — air-cleaning and fuel filters, sensor connector blocks; *b* — nozzle unit vanes, variable vane cages, igniter cases; *c* — units and vanes of nozzle blocks after repair of surface casting defects; *d* — honeycomb and metal-ceramic seals

alloys by brazing, the technology of which was developed together with Admiral S.O. Makarov National Shipbuilding University (Figure 6).

High-temperature powder braze alloy VPr11-40N and proprietary braze alloys NS-12, NS-12A were used in production. Foil braze alloys VPr-4 and VPr-7 are applied in addition to powder braze alloys. Depending on braze alloy type brazing temperature is equal to 1050–1180 °C.

Both in full-scale and in pilot production specialized shop sections were set up, fitted with vacuum equipment, devices and fixtures.

In gas turbine construction it is also necessary to weld large cross-section parts. For instance, guide vane rings, LPC, HPC flanges are made of martensitic-ferritic class steels using forged semi-rings with cross-sectional area of up to 14,500 mm^2.

Practically all the components, using rings, operate at high loads and increased temperatures, thus requiring the semi-ring welded joints to have operational properties not lower than the level of those of the base metal.

Semi-rings from 20Kh13, EP 609Sh, EI 961Sh and other steel grades were produced by mechanized CO_2 welding by bath method. However, multiple repairs of weld defects enhance the cost of part manufacturing. In order to improve the quality of welding forged semi-rings, the Enterprise introduced ESW technology. Earlier, some ESW features did not permit application of this technology, as it was necessary to create a technological «pocket» for the start of electroslag process, mount run-off plates for welding on the «discard head» at the end of welding, apply copper water-cooled plates to form the weld side surfaces.

As a result of research it was possible to simplify the part preparation for welding. Application of preheating up to 500–600 °C allows moving over from the arc to electroslag process already in the second pass so that in the presence of allowances there is no need for the technological pocket.

Shrinkage looseness at the end of welding is achieved owing to an operation similar to crater welding up in arc welding. At the final stage the welding head is stopped. Welding current and wire feed are smoothly decreased to zero. Thus, there is no need for welding on the «discard head».

Copper forming plates requiring fitting of the edges to be welded in each concrete case were replaced by ceramic ones based on Al_2O_3. Such ceramics can stand the liquid pool temperature and does not go into the weld, owing to the presence of a thin layer of slag between it and liquid pool metal. Easy treatability of ceramic plates and ability to glue them in the butt zone by a mixture of liquid glass with alumina, make this material a convenient substitute of copper plates, particularly at a great difference in their thickness.

Welding of martensitic-ferritic steel is performed by EP 609Sh welding wire of 4 mm diameter, using AN-318A flux. Weld metal composition meets the requirements of TU 14-1-2412–78, mechanical properties of weld metal and HAZ are higher than similar base metal values.

Engine life is determined by the duration of operation of the «weakest» component or part. Components and parts of the high-temperature section operate under hard conditions. Turbine blades belong to the most heavy-duty parts, determining the life of modern GTE.

Nickel-based high-temperature alloys ChS 70, ChS 88VI, ChS 88U-VI, containing chromium, tungsten, molybdenum, titanium, aluminium, boron and other elements, are mainly used for GTE blades. They combine high high-temperature strength of the above alloys, which is due to presence of complex-alloyed solid solution and maximum content of the strengthening phase with satisfactory adaptibility to fabrication. An alloy high-temperature properties are largely dependent on its structural states, grain size, shape and dispersity of the strengthening phases. Contact surfaces of blade flanges and edges wear during operation. Reduction of blade height promotes axial flowing over of gas with engine efficiency dropping by 1.5–3.5 %. Appearance of worn-out areas leads to formation of gaps and increase of the level of vibration loads, which may lead to blade fracture, and failure of the entire engine. The operating life of blades is determined by the degree of wear of contact surfaces of flanges and edges. However, despite the wear, the blade airfoil and root preserve their serviceability and after strengthening they can stand 3–4 operation life periods. In addition, worn earlier strengthened surfaces can be restored several times.

According to the earlier technology, strengthening of GTE blade edges and flanges was performed by nonconsumable electrode argon-arc hardfacing of stellite. The main disadvantages of this technology were cracking in the hardfacing zone (stellite–base metal) and non-uniform distribution of deposited stellite hardness over the area of the blade edge or flange.

Based on the new technology, trapezoidal electrodes ($3 \times 2 \times 2 \times 260$ mm) are made from plasticized high-temperature material KBNKhL-2 in SNVE 1.3.1/16-IZ vacuum furnace. Surfacing with these electrodes was performed by oxygen-acetylene flame, using GO2 manual torch (#2 tip) and PV-200 flux. Edges of blades from ChS 70, ChS 88VI, ChS 88U-VI alloys are hardfaced.

Oxyacetylene hardfacing provides a high metal quality without external or internal defects with stable hardness *HRC* 60 over the entire area of blade edge or flange. At present the plasticized mixture of high-temperature material KBNKhL-2 is produced in the Enterprise.

Introduction of the technology of strengthening the edges and flanges of GTE blades by oxyacetylene hardfacing of high-temperature material KBNKhL-2 allowed eliminating rejects, which are caused by development of cracks and other defects. This technology was used for manufacturing more than 180 electrode sets and strengthening of edges and flanges on more than 1000 blades.

GTE design envisages fastening flue tubes by locators. The majority of the locators are made of martensitic-ferritic steels 14Kh17N2 and EI 961, and for newer and more powerful engines (for instance, DN-80), they are made of nickel-based austenitic alloy EP 648.

To improve wear resistance, locator working surfaces are hardfaced with stellite. Selection of hardfacing material is due to a high operating temperature of parts (450–600 °C), as well as presence of considerable contact loads on these surfaces. Main requirements made to the deposited layer are absence of cracks (LUMA control) and deposit hardness ($HRC \geq 40$).

Earlier hardfacing was performed by manual AAW with cast rods of 3–4 mm diameter. This technology, however, has serious drawbacks. First, during hardfacing of 14Kh17N2 and EI 961 steels longitudinal cracks often form along the entire length of the deposit, propagating into the base metal. Stellite and martensitic-ferritic steel (for instance, 14Kh17N2) have different values of the coefficient of thermal expansion, so that cooling of the deposited part induces high stresses, and if the deposit has pores and inclusions, they become crack initiation sites. Secondly, part hardfacing is performed in two layers to ensure the required hardness of the deposited layer, as intensive mixing of stellite with the base metal takes place at AAW, which results in the hardness of the first layer not exceeding *HRC* 32–35. Two-layer hardfacing leads to extra consumption of expensive stellite and increase of labour consumption of part manufacture.

In this connection argon-arc hardfacing was replaced by plasma-powder hardfacing of cylindrical surfaces of tube locators in UPM-150D unit (Plasma-Master, Ltd.). Hardfacing is performed by high-temperature constricted arc, generated in a plasmatron with a non-consumable electrode. Range of adjustment of main arc current was equal to 25–150 A. Filler material is powder of Stellite 12 grade, the composition of which is identical to that of PRV-VZKR stellite. Argon was used as plasma, transporting and shielding gas. Design of drum type feeder ensures a uniform and precisely dosed powder feeding. In plasma-powder hardfacing of locators of 8 to 27 mm diameter, machining allowances can be smaller, which results in a good appearance of the deposit.

Introduction of the technology of plasma-powder hardfacing of stellite in the Enterprise improved the quality of the hardfaced parts and lowered the labour consumption in expensive part manufacture.

Technologies of electron beam spraying of heat-resistant and thermal-barrier coatings, plasma spraying and many other have also been mastered.

Thus, State Enterprise «Zorya»–«Mashproekt» has put into operation modern welding and related technologies, ensuring development and manufacturing of highly efficient GTU for various applications, competitive in the world market. The Enterprise welding production is currently capable of solving diverse technology tasks of any complexity.