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Electron beam welding – equipment and accessories

Abstract: Electron beam welding has been known and used for a long time, yet the recent years have seen increasing advancements in equipment fully utilising this welding method potential. Electron beam welding machines can be both universal and highly specialised, which can translate to significant operating and, first of all, welding costs reduction. Modern electron beam welding devices are provided with control systems and safety features which maximise operator's anti-radiation protection and enable carrying out technological processes in vacuum conditions.

Keywords: electron beam welding, welding machines, equipment, accessories, process control system

Introduction

Electron beam welding is usually carried out in a vacuum, yet there are also non-vacuum welding machines available. The principle of the electron beam welding process itself was presented in the authors' previous work [1]. Modern electron beam welding devices are controlled by PLCs equipped with working tables or numerically controlled welding positioners enabling the automation of welding processes and provided with various control and safety systems aimed to maximise the operator's protection against radiation and carry out technological processes in the vacuum.

Electron beam welding machines – irrespective of their size, intended use and manufacturer – are composed of four basic structural units [2]:
- electron beam generator,
- working unit (working, usually vacuum, chamber and system of manipulators),
- vacuum generation and control system,
- control system.

Such units can be produced in numerous variants, differ in many technical solutions and be highly customised, with customers' needs usually grouped as follows:
- short-lot production with frequently changing schedules of welding works,
- medium and big-lot production using highly automated welding processes,
- welding large-sized objects.

Depending on their intended use, electron beam generators can work at low (approximately 60 kV) or high voltage (above 60 kV). Low-voltage generators are usually cheaper, whereas high-voltage generators provide a very convenient weld shape coefficient (width-to-depth ratio 1:20) and, at the same time, enable carrying out welding even if the distance between the workpiece and the welding machine electron gun is considerable [2].

The design solution of a working unit depends on the indented use of a given device. The basic type of such a unit is a universal working chamber along with equipment which

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enables welding large-sized workpieces as well as small lots of very diversified and small-sized elements. This solution is usually applied in laboratory devices or in machines used in diversified production.

Another type of an operating unit is the working chamber equipped with an appropriate manipulator, adjusted to the size and shape of workpieces. As a result, it is possible to reduce time necessary for generating the vacuum in the working chamber. Another advantage, in the case of a stroke working table, is the fact that activities connected with loading and unloading individual table pockets do not depend on the welding process and do not extend the total time of a single welding cycle.

Devices for welding large-sized elements can be equipped with working chambers of significant volume, e.g. 600 m3 or chambers with local vacuum. In relation to such elements the process of welding can also be carried out at atmospheric pressure [2].

The vacuum system should ensure possibly short time of vacuum generation in the welding machine working chamber (high pump-out rate) and appropriate working pressure in the welding area and electron gun.

The electron beam welding machine control system is in each case adjusted to a specific device. As a rule, the electron beam welding process control is carried out without the direct participation of the operator, who only sets up welding parameters and decides about welding process commencement [2].

Figure 1 presents an exemplary electron beam welding station with basic components. The working chamber is made of unalloyed steel. Depending on the value of maximum electron gun accelerating voltage additional lead sheet screens of the working chamber can be used. Working chamber internal walls are usually provided with additional screens (easy to disassemble and clean) made of thin austenitic steel sheets aimed to protect the chamber interior against settling vapours of metals generated during welding processes. The electron gun can be positioned horizontally or vertically or be fixed inside the chamber on a dedicated manipulator. The electron beam welding machine working chamber is usually stationary. However, in special cases it is possible to carry out welding processes using a mobile local vacuum chamber fixed on the surface of a big-sized workpiece not performing working motion.

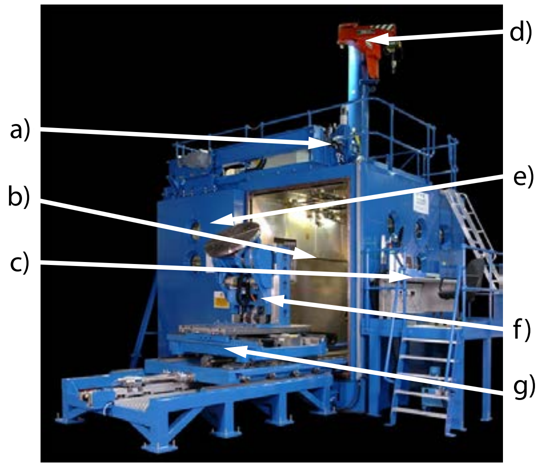

Fig. 1. Example of complete electron beam welding station, a) electron gun, b) vacuum working chamber, c) control system, d) manipulator, e) working chamber sliding door, f) welding positioner, g) CNC table

It should be emphasized that today's devices for welding and surface processing using an electron beam as a welding heat source are additionally equipped with many accessory systems aimed at facilitating operator's work conditions, improving welded joint quality and increasing welding device efficiency.

Division of electron beam welding machines

Depending on intended use the market offer of electron beam welding machines is vast. The selection of a given device is dictated by many factors such as the type of material to be welded, the size, shape and weight of workpieces, expected welding process efficiency and whether the process will be carried out autonomously or as part of a technological line. Taking into consideration all factors makes it possible to design and produce a device in a manner enabling the obtainment of the required quality of workpieces and reduction of operating costs. Electron beam welding machines can be universal or specialised, i.e. designed for welding specific types of elements.

Due to technological, production-related and metallurgical requirements electron beam welding solutions include the following machines [3]:

- universal high pressure welding machines, with a gun fixed inside or outside the working chamber. After appropriate tooling modification such devices enable welding a vast range of products and elements;
- special high pressure welding machines, intended for welding specific elements such as, for instance band saws, toothed wheels, turbo-compressor rotors;
- reduced pressure electron beam welding machines (RPEB) with local chambers fixed on a structure being welded. The electron gun is located outside a local chamber of small volume, covering only a section of a flat or girth joint being welded, e.g. of storage tanks. The vacuum is only maintained in the small chamber. Such a solution minimises the time needed to generate the vacuum;
- non-vacuum electron beam welding machines (NVEBW). The electron beam is generated in high vacuum and at high accelerating voltage of 150-220 kV. The beam is moved towards the workpiece by the system of vacuum passes, i.e. the system of nozzles gradually reducing vacuum to atmospheric pressure. Welding at atmospheric pressure almost entirely eliminates problems related to the size of a structure being welded. The NVEBW machines are provided with high-efficient pumps and special electron beam discharge orifices to ensure the highest vacuum decrease gradient between the electron gun and atmosphere.

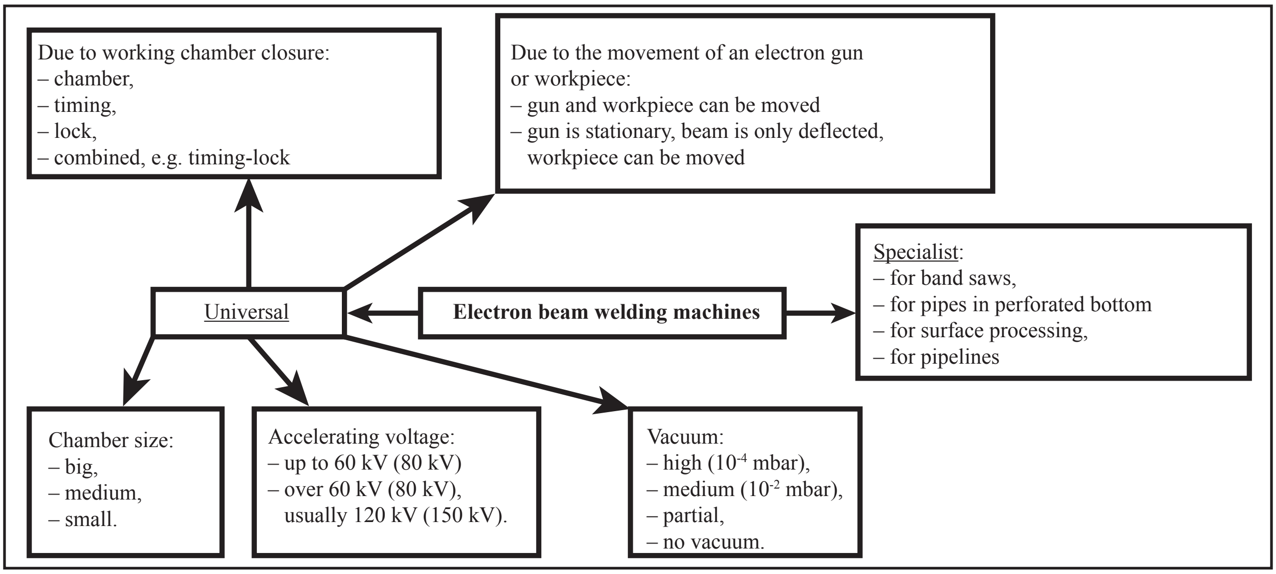

Fig. 2. Division of electron beam welding machines

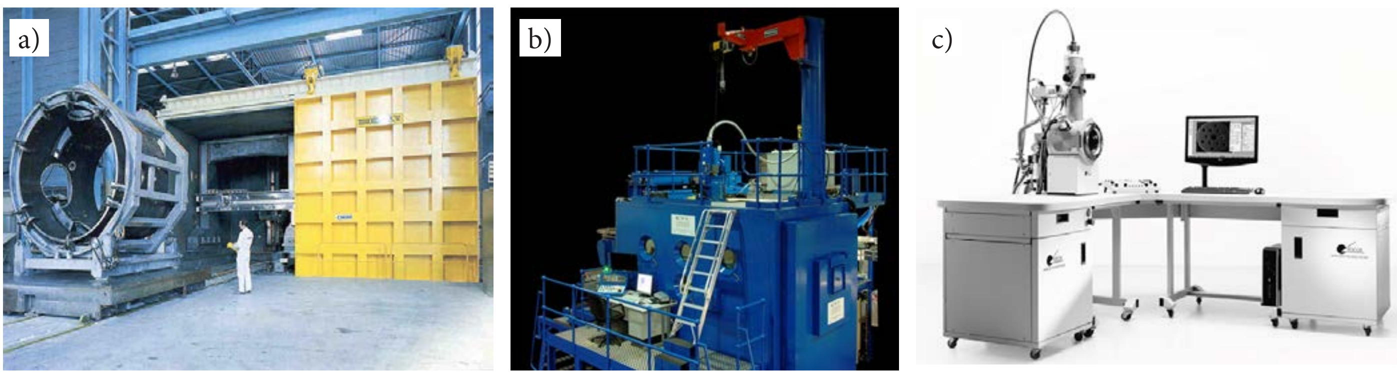

Fig. 3. Examples of working chambers a) big, b) medium and c) small [4, 5]

Figure 2 presents the division of electron beam welding machines. Examples of electron beam welding machines based on various working chambers are presented in Figure 3. Figure 4 presents the schemes of equipment design in relation to welding process pressure. In turn, Figure 5 presents the types of devices due to working chamber design. In most solutions the electron gun is motionless in relation to the workpiece. However, in special cases it is possible to use a device with a moving gun fixed on a manipulator (Fig. 6). As was described above, it is also possible to use welding machines with a local vacuum working chamber (Fig. 7) or non-vacuum machines (Fig. 8). The market offer also includes special design or customised welding devices such as, for instance, a subsea pipeline welding machine developed within an international research programme (Fig. 9).

a) b) c)

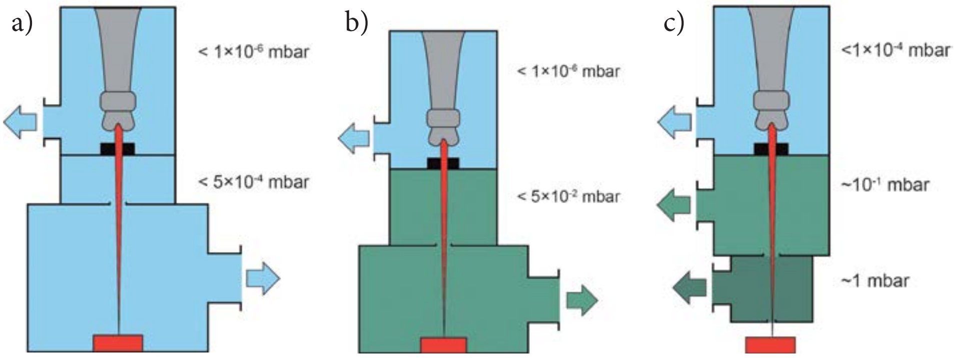

Fig. 4. Schemes of electron beam welding machines due to working chamber vacuum a) high vacuum, b) medium vacuum c) welding under atmospheric pressure [6]

a) b) c)

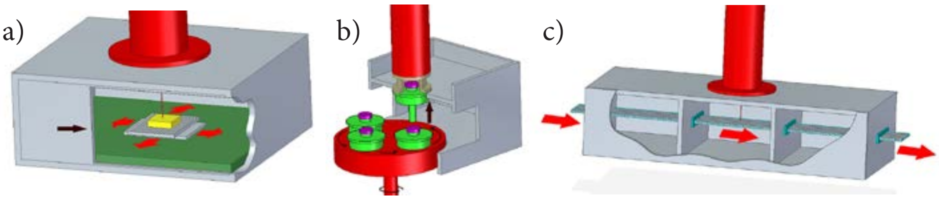

Fig. 5. Types of electron beam welding machines due to working chamber design a) universal welding machine with a big volume chamber, b) stroke welding machine, c) continuous operation welding machine (lock) [6]

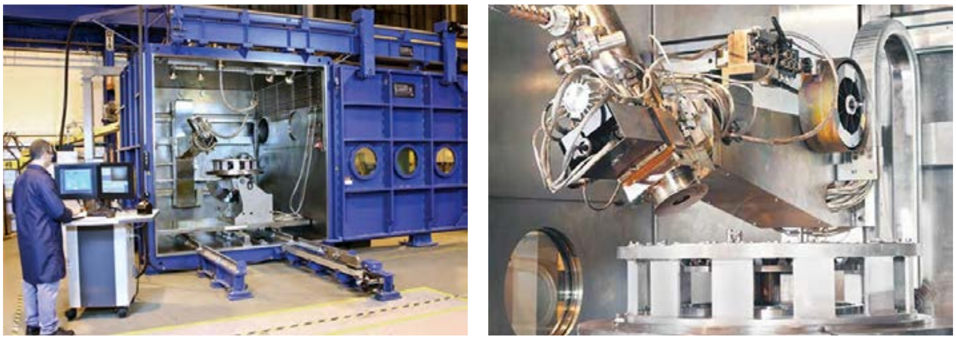

Fig. 6. Example of a Sciaky-manufactured electron beam welding machine with a moving electron gun [7]

Fig. 7. Example of an electron beam welding machine with a local chamber [8]

Fig. 8. Non-vacuum electron beam welding machine, P=24.5 kW, U=175kV [9]

Fig. 9. Example of a specialist electron beam welding machine for welding subsea pipelines [10]

Additional equipment of electron beam welding devices

As regards increasing the welding process efficiency, ensuring the best quality of welded joints and facilitating operators' work, electron beam welding equipment manufacturers offer many additional systems, including the following [11]:

- automatic beam correction system,
- CCD camera-based welding area monitoring system,
- welding area monitoring system using back-scattered electrons,
- automatic joint axis tracking system,
- automatic process control system,
- automatic joint quality control system.

Automatic beam correction system

One of the most important preventive measures enabling the obtainment of the highest quality welded joints is the proper electron beam correction. Growing demands for joint quality are accompanied by similar requirements as regards the quality of electron beam. The primary issue is focusing a beam on the surface of a welded workpiece using the smallest possible diameter and the highest available power density. In order to minimise the movement of a beam having the highest power density along with the change of focus, the electron beam must be centred in the optical axis of lenses. Electron guns, particularly those of high power, are additionally provided with a system enabling the elimination of possible electron beam astigmatism and obtain an axially symmetrical beam. After conducting all correction stages, the electron beam power density distribution should correspond to the Gaussian curve, which guarantees the obtainment of best quality joints. Ensuring the proper beam shape is particularly important in industrial-scale electron beam applications. If an electron beam welding device is just one element of a technological line, the process-operating personnel usually do not have sufficient knowledge and have not had adequate practice in terms of proper electron beam calibration. The result obtained in such a case may significantly differ from the optimum solution, which, as a result, fails to guarantee the repeatability of welding process. In addition, in practice, often even experienced equipment operators are unable to properly conduct electron beam correction. The comparison of results achieved by inexperienced and experienced operators and those obtained using the automatic system is presented in Figure 10.

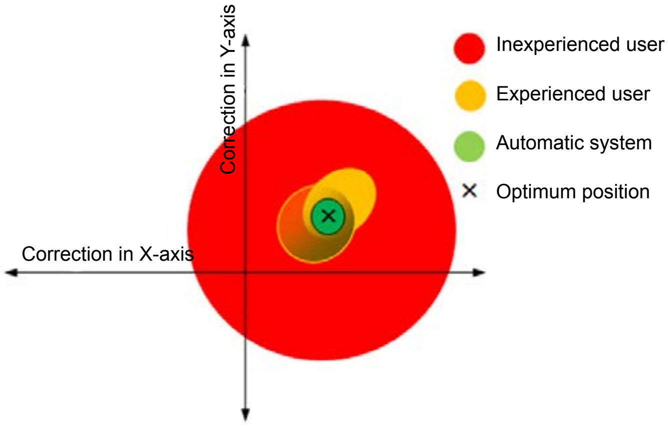

Fig. 10. Centring and removing astigmatism has two basic parameters, i.e. calibration in X and Y axes. An error in both axes generates the area of an improperly positioned beam [11]

Welding area monitoring

The monitoring of a welding area in the vacuum working chamber can be conducted using either of the two techniques:

- optical method,
- electron-optical method (EO).

The first method utilises a CCD camera for observation. The disadvantage of the method is its sensitivity to the reflection of light against "mirror" surfaces. The second method utilises back-scattered electrons, similarly as in a scanning microscope (SEM). An electron beam scans the surface of a welded or processed workpiece and back-scattered electrons generated from each point of the electrode are recorded by sensors. The contrast of images obtained is 1:15000. The EO-based system advantage relies on its insensitivity to light reflections, high detail detectability (Fig. 11) and the possibility of differentiating between various materials. Figure 12 presents the comparison of two images of the same element recorded with both methods.

Fig. 11. Example of an image recorded using back-scattered electrons [4]

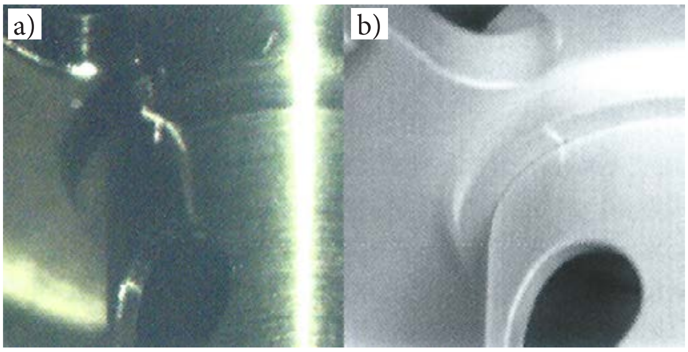

Fig. 12. Comparison of the same surface image recorded using a CCD camera (a) using back-scattered electrons (b) [11]

Automatic joint axis tracking system

In industrial practice electron beam welding is usually used for making girth welds. A particular feature of the joint axis tracking system is, in this particular case, the possibility of observing a weld on a plane, which facilitates process monitoring and detection of potential imperfections. An example of using the system for welding pressure sensors is presented in Figure 13.

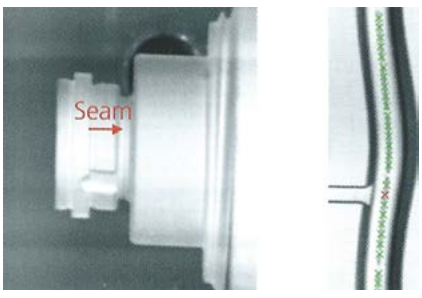

Fig. 13. Example of a joint axis tracking system using back-scattered electrons during welding a pressure sensor [11]

Joint axis tracking systems utilising the electron-optical method are also used for geometrical measurements, which enables setting corrections during welding. The system can monitor a joint several metres in length with the accuracy of 0.1 mm. Such monitoring is used, e.g. during the production of radiator elements [11].

Welding process control system

Similarly as in the case of welding area monitoring system also the welding process control can be carried out using two methods, i.e. optical and electron-optical. Such a system is used for detecting spatters during welding as well as for monitoring a weld key-hole and metal melting process. The EO-based systems are not sensitive to reflections from the workpiece surface and also make it possible to detect some welding imperfections as they emerge [11].

Joint quality control system

Joint quality control methods are many and varied. One of them is monitoring beam parameters. Another solution is based on back-scattered electrons enabling the workpiece surface quality control and detection of excess penetration, lack of penetration, undercut or spatter. Additionally, after welding it is possible to use X-radiation for detecting internal joint imperfections, e.g. gas pores [11].

Working chamber equipment

In order to fully utilise the potential of electron beam welding or surface processing it is necessary to use additional tooling, particularly if a welding machine is equipped with a stationary electron gun (electron beam movement is then possible only by means of coils deflecting in a very limited range). The basic tooling includes:

- X-Y CNC table (Fig. 1),
- disc or roller welding positioner (Fig. 1, 14),
- manipulator,
- electrode wire feeding system (Fig. 15),
- positioners and clamps,
- beam control systems.

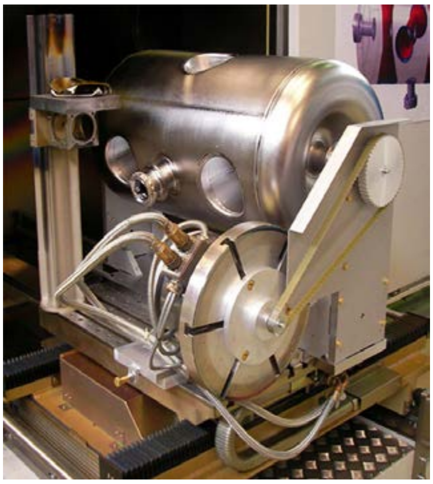

Fig. 14. Example of using a welding positioner during electron beam welding of a girth weld in a container made of 4 mm thick RR300 niobium alloy [12]

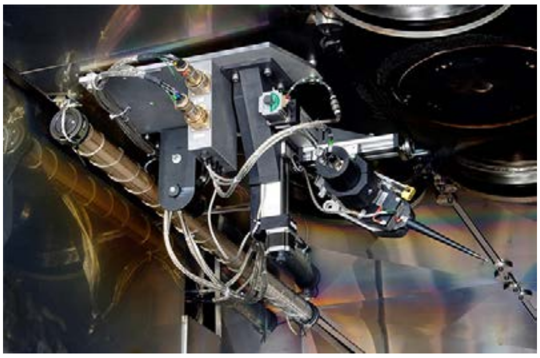

Fig. 15. Electron beam welding electrode wire feeding system [4]

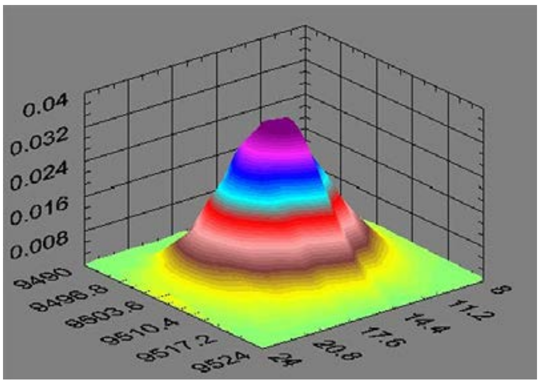

Fig. 16. Electron beam power density distribution

Fig. 17. Electron beam quality control device diaBEAM by Aixact [14]

Beam control systems

In the case of an electron beam it is essential to maintain the proper symmetry of power density distribution. Even slight differences can generate imperfections in welded joints. Figure 16 presents electron beam power density distribution composed of a high-density core and a rim characterised by lower power density. Beams of the same diameter can thus provide entirely different welded joint quality. An excessively wide rim of excessively high power density can generate an excessively wide heat affected zone or an improper weld shape [13].

Although, as standard, electron beam welding devices are equipped with beam quality control systems, in many cases it appears necessary to verify whether a given beam is characterised by proper parameters [14, 15]. Such a necessity usually follows the replacement of a cathode or the failure of a device. Also, the electron beam profile can change due to the following reasons [13]:

– changes in workpiece position in relation to the beam,
– power supply system instability,
– tooling damage.

Beam parameters which can be defined using external control systems include, among others, the following:

Fig. 18. Electron beam quality control device Probe Beam by CVE [13]

- beam diameters,
- FWHM (Full Width at Half Maximum), beam width at 50% power,
- FWe2, (Full Width at $1/e^2$) beam width at 13.5% power,
- beam density distribution,
- beam symmetricalness.

The systems are composed of a sensor and a system for collecting and archiving data. Specialist software enables the presentation and analysis of collected data. An example of a beam control device is a diaBEAM system (Fig. 17) developed by Aixact or Probe BEAM (Fig. 18) manufactured by CVE.

Manufacturers also offer devices which monitor welding processes in real time or facilitate controlling the quality of electron beam itself. Such equipment is usually operated via a "user-friendly" control panel enabling setting required welding process technological parameters and informing about the present status of individual components indicating exceedings of permissible limits. In addition, modern devices enable the on-line diagnostics of device operation, which significantly facilitates communication with the manufacturer's service department and quickens the removing of failures.

Summary

The versatility of the market offer makes electron beam welding, despite available laser beam welding solutions, increasingly popular for joining thick elements or materials impossible to weld using other welding technologies. Manufacturers in conjunction with research establishments such as Instytut Spawalnictwa can offer a welding device along with related technology. An important factor is the possibility of customising devices, optimising the shape and size of working chambers, selection of pumps and, most importantly, making precise electron guns. Electron beam welding machine designs enable carrying out processes using a local chamber or at atmospheric pressure. Such devices can be provided with various welding positioners, CNC tables and electrode wire or flux feeding systems. During electron beam welding the electron gun can be operated vertically or horizontally. It is also possible to make joints in restricted positions. Presently used electron beam welding machine designs maximise personnel protection against X-radiation. Even devices with accelerating voltage of 150 kV pose no threat to operators. In addition, electron beam welding machines are equipped with a number of systems facilitating work and significantly improving the quality of joints, e.g. welding area visualisation using back-scattered electrons.

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