Condition, Development, Potential and Application of Electronic Treatment

Stefan Kirilov Kartunov
Technical University of Gabrovo
Emeritus Prof. Department Mechanical Engineering
Bulgaria, Gabrovo
skartunov@abv.bg

Milan Vesković
University of Kragujevac
Faculty of Technical Sciences
Serbia, Čačak
milan.veskovic@ftn.kg.ac.rs

Abstract—**The report provides a historical overview of the topic, examines the physical basis of electron beam production, thermal emission and treatment area, types of electron beam treatments and the state of technology, types, development and potential of equipment and its application in practice. The advantages and disadvantages are analyzed and the main conclusion is made that the wavelength of the beam determines and is commensurate with the resolution and size of the processed components.**

Keywords- electron beam treatment; beam wavelength; resolution;

I. INTRODUCTION

Methods of radiation treatment have been developing intensively in the last 30-35 years of the XX century. In many cases, their application is the only possible and directly determine the progress of mankind. They do not have the issue of tool wear, because such is the focused beam. Radiation treatment methods are characterized in that the removal of the material is performed by the direct conversion of the energy of light, electron beams and plasma jet into heat in the treatment area. The material is heated and evaporated in a localized area. This is achieved by acting on the workpiece with concentrated beams with high energy density. Therefore, these methods are also known as high energy processing methods. The possibility of accurate dosing of energy allows a wide range of technological operations: local heat treatment, cleaning and welding, machining, changing the structure of materials and others.

The types of radiation treatment are: Electron-beam treatment; Laser beam treatment and Plasma jet treatment.

The processing of materials by energy radiation methods began in 1905 of the XX century, when Pirani (Siemens AG Germany) patented a method for melting materials in vacuum by electron beam irradiation [1]. The electron beam melting method1 was invented in 1907, but until 1950 it was only used to melt refractory metals. Then it takes about 35 years before the first prerequisites for the technical and economic application of this method. In 1942, Borries patented an electronic-optical device for drilling holes [2], and in 1948 the German scientist Stegwar invented the first equipment for electron beam processing [3]. However, it took almost another 20 years for the electron beam to be widely used in manufacturing (initially for material removal and welding). In 1949-50 in the company Zeis (Germany) K. H. Steigerwald began systematic research into the heat treatment of materials by electron beams [4]. These works led to the development of machines for electron beam processing by welding and cutting. The first electron beam welding machine became operational in 1958. The American inventor James T. Russell was also recognized for designing and building the first electron beam welder [5]. In the 1960s and 1970s, electron beam treatment was further developed through the use of combined methods (eg evaporation), and after 1970 as non-thermal methods for microstructuring and processing of artificial materials (polymers). In 1980, an electronic rifle1 with a capacity of 600kW was produced and development continues [6].

II. EXPOSURE

The physical basis of the method is based on the use of the energy of a concentrated electron beam for rapid melting and evaporation of the material. Electrons with an energy of about 100 keV are stopped by a sufficiently thick material (for example steel), in which almost 100% of their kinetic energy, practically without loss of time, is converted into heat in the surface layer of the irradiated body. By means of electron-optical means, the electron beam is focused with a high energy density. Under vacuum, using the electronic pistol after acceleration, focusing on the energy density of $10^6 \sim 10^9$W/cm^2 extremely narrow beam with high-speed minimal impact on the surface of the part and in parts of the microsecond thermal energy. Currently, the electron beam has an energy density P of up to several million kW/cm^2.
($P = 1.10^8$ W/cm^2; for comparison, the density of the laser beam is up to $P = 1.10^{19}$ W/cm^2).

In addition to the properties of an intense light source, the electron beam also offers extremely good control options. The intensity, shape and position of the beam are maintained very precisely and, if necessary, changed practically easily. Electrons do not have a chemical nature of their substance (unlike ions) and do not contribute to chemical alteration of the processed materials.

The application of: coherent beam; from accelerated electrons (Ve ~ 1/3 Vsv., At 300 kV - Ve = 0.6 Vsv.) serves for heating, melting, evaporation and changing the chemical composition of materials.

Principle of receiving the beam

High power Brown tube is used for: heating to evaporation of the cathode, emission of electrons, acceleration by electric field when applying voltage from 30 kV to 1200 kV (most often 150 kV - 300 kV) and focusing of the electron beam [7] (less than 10 μm. Magnetic fields are used to focus and position the electron beam. Deviation from an angle of $\pm 15^0$ can be achieved by inductors) (Figure 1).

The temperature in the processing zone is about 60,000 C, due to which the material evaporates. To limit the heating zone, the pulse generator provides interruption of the electron beam, and the electromagnetic control device stabilizes it. The pulse generator operates with a frequency of 1 Hz to 3000 Hz – 5000 Hz, which provides a pulse duration of 10 ms to 50μs. Thus, the irradiation time is hundreds of times less than the time during which the part is not irradiated and cooled. The contact of the electron beam with the material leads to the production of X-rays, so measures must be taken to isolate them. With the help of the electromagnetic lens, the rays are focused to the diameter of the flow, equal to the diameter of the drilled hole. The electromagnetic diverter moves the electron flow along the workpiece surface. The treatment is carried out in vacuum (not lower than 66.10-3 N/m^2, 133.10-4 N/m^2 and most often 133.10-6 N/m^2), which is a prerequisite in order to obtain a concentrated flow of electron beams. This allows for additional cleaning of the treated surface. The processing time depends on the thermal and chemical properties and the amount of material removed. Its mechanical properties do not significantly affect the processing time. Figure 1 shows a schematic diagram of an electron beam treatment system [7, 8].

A. Thermoelectronic emission

The thermoelectron-emission from a heated cathode is determined by the chaotic motion of electrons in a metal conductor (so-called "electron gas"). It is explained by the theory of the kinetic energy of gases. According to her, the thermal velocity and energy of the electrons depend on the absolute temperature *T* of the emitting cathode material. According to the Maxwell-Boltzmann distribution law for the average velocity v_h we get:

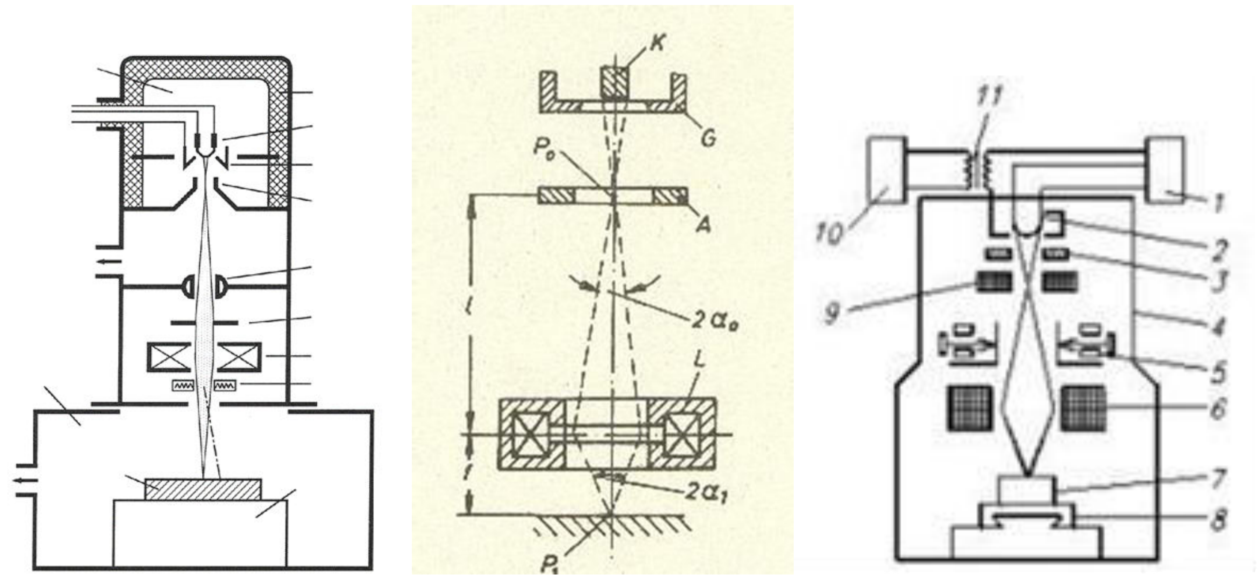
$$\frac{m_e v_h^2}{2} = kT \qquad (1)$$

where m_e is the mass of the electron at velocity v_e, k is the Boltzmann constant. k = 1.38*10-23 Ws/K The kinetic energyof the electron beam is:

$$E_k = \frac{mv^2}{2} \qquad (2)$$

$$v = \left(\frac{2q}{m_0 U_a} \right)^{\frac{1}{2}} \qquad (3)$$

where U_a is the accelerating voltage, kV; q is the electron charge, C; m_0 is the mass of an unexcited electron.



a) *b)* *c)*

Fig. 1. Electron-optical tube and optical system of a system for processing materials with an electron beam

Legend: 1, 3-vacuum pump; 2-working camera; 4-high voltage; 5-electron tube; 6-insulator; 7-cathode, electron beam source; 8-electrode; 9-ring anode; 10-pass valve of the pulse generator; 11-electromagnetic control aperture; 12-magnetic focusing lens; 13-electromagnetic deflection device (coil); 14-work table; 15-detail.

Formula (3) only applies to very low electron velocities and therefore:

$$E_k = \Delta m_e c^2 \qquad (4)$$

where Δm_e is the increase in the mass of the accelerated electron compared to that in its unexcited state; c - speed of light, km/s.

$$m_e = \frac{m_0}{\left[1-\left(\frac{v_e}{c}\right)^2\right]^{\frac{1}{2}}} \quad (5)$$

For kinetic energy we get:

$$E_k = qU_a \quad (6)$$

For $v_e = 0.6\,c$, an accelerating voltage of 128 kV must be applied. Then the mass of the electron is 1.25 m_0 [5].

If we equate the kinetic energies in the left parts of equations (1) and (6), the following expression is obtained:

$$qU_T = kT \quad (7)$$

Where U_T is the temperature potential (index T indicates that it refers to thermally acquired energy), V.

Equation (7) can be used to determine the energy required for complete evaporation of a material at a given evaporation temperature (eg for a barium cathode at T = 1161 K the energy qU_T = 0.1 eV and the tungsten cathode at T = 2900 K energy eq. U_T = 0.37 eV). The average statistical width of the spectrum is taken into account. The maximum width is about three times larger.

The emission current density is:

$$j_s = a^2 Tq - \frac{A}{kT} \quad (8)$$

Wherein a is the constant for pure metals, for example 120 A/(cm^{2}K); T - absolute temperature, K; A - the work done to emit electrons of different materials, eV;

for example: for W - 4.5 eV, for Mo - 4.4 eV, for Ta - 4.3 eV.

At electron beam power P = 3 kW, accelerating voltage U_a = 150 kV, current I = 20 mA, thickness d = 0.1 mm and cathode area F = 0.8 mm^2, the emission current density is j_s = 2, 5 A/cm^2.

B. Processing area

The theoretically achievable processing diameter is small (d_{min} = 1-2 μm), but in practice it is 0.1 mm - 0.8 mm. The minimum diameter of the electron beam processing area is determined by the beam focusing and control system. The focusing and control system shown in Figure 1b consists of a cathode K controlling the cylinder G for concentrating the beam, an anode A and an electromagnetic lens L. It is assumed that the calculation is performed for a section in the form of a circle in the transverse direction of emission. The radius of the radiating area of the cathode is r_k. The focusing scale (reduction) M is set by the ratio l/f, respectively by the ratio a_0/a_1:

$$M = \frac{1}{f} = \frac{a_0}{a_1} \quad (9)$$

where f is the distance between the magnetic lens and the working area, mm; l - the distance from the anode to the plane of the lens, mm; a_0 is the angle of scattering of the beam from the source side, 0 and a_1 is the angle of focus of the beam exiting the lens towards the part, 0.

Table 1 shows the machining diameters for different technological operations and accelerating stresses.

TABLE I. DIAMETER OF ELECTRON BEAM PROCESSING AT DIFFERENT METHODS AND VOLTAGES FOR ACCELERATION

Processing operations	Accelerating voltage, kV	Processing diameter, mm
Welding	**15 - 75**	**0,100 - 0,500**
Melting	**15 - 40**	**0,010 - 0,050**
Evaporation	**10 - 40**	**0,010 -0,030**
Heat treatment	**30 - 150**	**0,005 - 0,100**
Chemical treatment	**20 - 5000**	**0,010 - 0,300**

C. Drilling and cutting

Materials up to 100 mm thick with a shape ratio of 100: 1 can be drilled and cut. The achievable depth h is determined by formula (11):

$$h \approx \frac{U_a^2}{\rho} = 0.030 \div 0.180 \text{ mm} \qquad (10)$$

where ρ is the density of the material, g/cm^3, U_a - accelerating stress, kV.

The following parameters are achieved when drilling with an electron beam:

- diameter 0.1 mm - 0.8 mm, min from 1 µm -10 µm (in special cases 0.05 mm - 1.2 mm)[6];
- processing time (0.02-3) ms/hole at productivity 2000 mm/min;
- positioning accuracy ± 0.025 mm.

Electron beam drilling is applied at small wheelbases with a large number of holes.

Examples: - perforation of titanium sheet metal for tanks for transporting and refueling aircraft (30,10^6 holes/m^2);

- perforation of masks for color TVs (2,106 holes/m2);
- nozzles in spinning machines (12000 holes with a diameter of 0.5 mm - 0.9 mm at a depth of 4 mm are drilled in 40 minutes);
- combustion chambers, gas burners;
- drilling holes in precious stones used for bearings in watches;
- openings of thread guides in the production of artificial fibers.

Cutting is applied:

- for cutting ferrites for memories;
- when expressing thin elements of difficult-to-process materials.

D. Electron beam welding

Electron beam welding (EBW) is a fusion welding process in which a beam of high-speed electrons is applied to two materials to be joined[7]. Electron beam welding is spot or seam welding. The principle of operation in welding is as follows: In the place of radiation from the electron beam, with sufficient power and energy density, a molten layer is formed (see Table 3). Ultra-high temperatures in this type of welding work are achieved by electrons moving in the vacuum chamber at a speed[3] of about 165,000 km/s. If the energy density increases, for example by better focusing the beam, at the point of direct impact and especially at its center, the vapor produces local, increased pressure. Equalization of this pressure with the hydrostatic pressure of the melt results in a crater of the molten surface layer to a depth of about 3 mm. The lower part of the melt is deformed in the manner shown in Figure 2. With a further increase in energy density and processing temperature, the vapor pressure increases and leads to the formation of a capillary wrapped in a layer of molten material through which the electronic beam penetrates deeper into the detail. This is a deep welding effect. If only the thermal conductivity at the irradiation site is used, a melt with a shape coefficient similar to that of conventional welding is obtained. The quality of welding depends on the type of paired materials, the shape of the welded parts, the parameters of vacuum and beam (accelerating voltage, current density, focusing). The main parameters[3] that determine the mode of operation include: Accelerating voltage; Amount of current in the emitted beam; Speed of movement of the beam on the surface of the welded part; Beam focusing accuracy; Duration of pauses and impulses; Degree of vacuum.

By changing the parameters of the process, different ratios of the depth and penetration of the width of the seam can be obtained.

The advantages of electron beam welding are:

- universality - all metals are welded;
- through the effect of deep welding small local molten and thermally conductive zones are obtained;
- highest welding speed compared to other high energy methods (5000 mm/min at depth 3 mm, 4000 mm/min at 4 mm, 3500 mm/min at 5 mm, 2800 mm/min at 6 mm, 1200 mm/min at 10mm); Due to the high energy concentration, metal up to 20 cm thick can be welded in only one pass;
- very high efficiency, which allows to consume 10 or even 15 times less energy without the need for shielding gas or additional material; The efficiency of electron beam welding is 85 % - 95 % and it remains the most economical and accurate welding method.
- easy to automate beam control allows welding of hard-to-reach places on the details in a safe way;
- high repeatability of dimensions in the production of new and restoration of old parts.

The disadvantages of electron beam welding are:

- applicability only in vacuum, due to which it has the best economic efficiency in mass production;
- X-ray protection and adjustment time required;
- requires very precise preparation of the seams; Cavities may form at the base of the seam, leading to poor performance;
- artificial materials and glass are not welded;
- Nitride or galvanic coatings cannot be applied to welds.

Table 2 compares the welding of different metals and alloys [6]. If pulsed rays are used, which have a higher density of radiated energy, as well as an increased frequency of up to 500Hz, it is used for welding volatile metals. These include aluminum and magnesium.

Application in practice:

Welding of cutting bands for band saw machines and parts for various drives, for high quality welds on sensitive materials for nuclear reactors, for emergency welding of precision parts of aircraft and rocketry, micro welding in the microsystem technique. It is also used in welding high-strength alloys and titanium-based alloys, as well as metals such as molybdenum, tantalum, niobium, tungsten, zirconium, and beryllium.

TABLE II. EVALUATION OF THE COMPATIBILITY BETWEEN METALS AND ALLOYS IN ELECTRON BEAM WELDING

	Zr_2Sn	$V_{10}Ti$	V	Ti	$Ni_{15}Cr_7Fe$	Ni	Nb	$Fe_{18}Cr_8Ni$	$Cu_{20}Ni$	Cu	Al	Ag
Ag	4	4	1	1	1	4	4	1	1	4	1	4
Al	4	4	4	4	3	1	4	3	3	3	4	
Cu	4	2	1	4	1	2	4	1	4	4		
$Cu_{20}Ni$	4	3	3	4	1	4	4	1	4			
$Fe_{18}Cr_8Ni$	4	4	2	4	1	1	4	4				
Nb	3	1	1	1	4	4	4					
Ni	4	4	4	3	1	4						
$Ni_{15}Cr_7Fe$	4	3	3	4	4							
Ti	1	4	3	4								
V	4	4	4									
$V_{10}Ti$	4	4										
Zr_2Sn	4											

Note: 1 - good, 2 - satisfactory, 3 - bad, 4 - unexplored..

E. The electron beam as a tool for heat treatment

If electrons fall at a certain speed on a solid body, they give their kinetic energy to the part in the form of heat. The impact after this initial effect depends on the ratio of the electron beam parameters such as total power, density, duration of treatment on the one hand and the thermal properties of the treated material such as heat absorption, relative and absolute boiling and evaporation points, thermal conductivity on the other. Thus, different electron beam treatment methods are obtained, shown in Table 3.

TABLE III. ELECTRON BEAM PROCESSING METHODS.

Method	Beam exposure time, s	Energy density, W/cm^2
Polymerization of lacquer materials	1.10^{-3} - 0,1	10 - < 1000
Sealing of integrated circuits	$1.10^{-6} – 1.10^{-3}$	100 - 1000
Drilling of artificial materials	10.10^{-6} - 0,05	1000 - 10000
Hardening of carbon steels	1.10^{-3} - 1	1000 - 10000
Melting of all metals, alloying	1.10^{-3} - 1	$1.10^4 – 1.10^6$
Welding	1.10^{-3} - 0,1	$1.10^5 – 1.10^6$
Drilling, perforation	10.10^{-6} - 0,1	$1.10^6 – 1.10^8$
Engraving	$(1 – 50).10^{-6}$	$1.10^7 – 1.10^8$
Sublimation	$(1 – 50).10^{-6}$	$1.10^9 – 1.10^{10}$

As can be seen from Table 3, higher power plants are required for melting, evaporation and heat treatment. Figure 3 shows a system developed by the Manfred von Ardennes Institute and VEB LEW (Germany) with an adjustable power P of 1200 kW, 250 kW and 80 kW and an accelerating voltage U_a of 38 kV, 30 kV and 20 kV. Shielding gas welding can also be performed, but then the pressure in the chamber is much higher and is a little over 100 Pa.

Electron beam welding is performed in a special chamber from which the air is pre-drawn3. The electron beam installation is equipped with a magnetic lens designed to generate a focused flow of electrons and effectively control it. There is also a loading hatch for feeding the welded parts (Fig. 4). Electron beam welding is performed with low voltage alternating current. It passes through a special focusing element (lens), where the cathode and anode are located and thus creates an electron flow with the specified characteristics. Depending on the design characteristics of the installation, electron beam welding can be performed by moving the material to be welded perpendicular to the fixed beam, or vice versa, the beam can move relative to the fixed part.

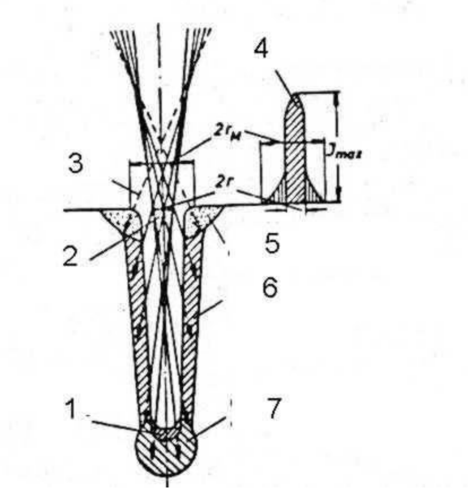


Figure 2. Capillary formation during electron beam welding

Legend: 1-withdrawal zone; 2-core rays, 3-peripheral rays; 4-intensity distribution in the radiation plane; 5-heated area of peripheral rays; 6-heated area of divergent rays; 7-heated area of thermal conductivity.

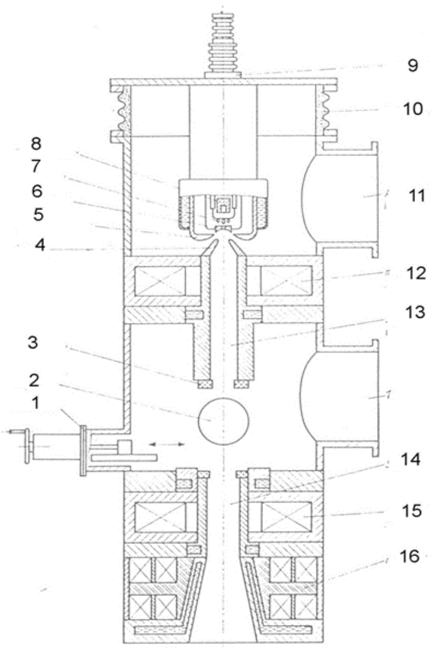


Figure 3. High power plant for melting, evaporation and heat treatment.

Legend: 1-way valve; 2-hatch for observation; 3-centering ring; 4-anode; 5-focusing electrode; 6-mass cathode; 7- wire - cathode; 8-ion trap; 9-power supply; 10-insulator; 11-flange for the vacuum pump; 12-magnetic lens; 13-current resistance I; 14-current resistance II; 15-magnetic lens; 16-magnetic deflection system.

In addition to the listed operations, the electron beam is applied in electron beam lithography and deposition of thin layers on the substrate or on the previous layer, described in detail in [2] and [7, 8]. Electron beam treatment is used in industry mainly for three product modifications[4]:

- Crosslinking of polymer-based products to improve mechanical, thermal, chemical and other properties,
- Degradation of materials, often used in the recycling of materials,
- Sterilization of medical and pharmaceutical goods [9].

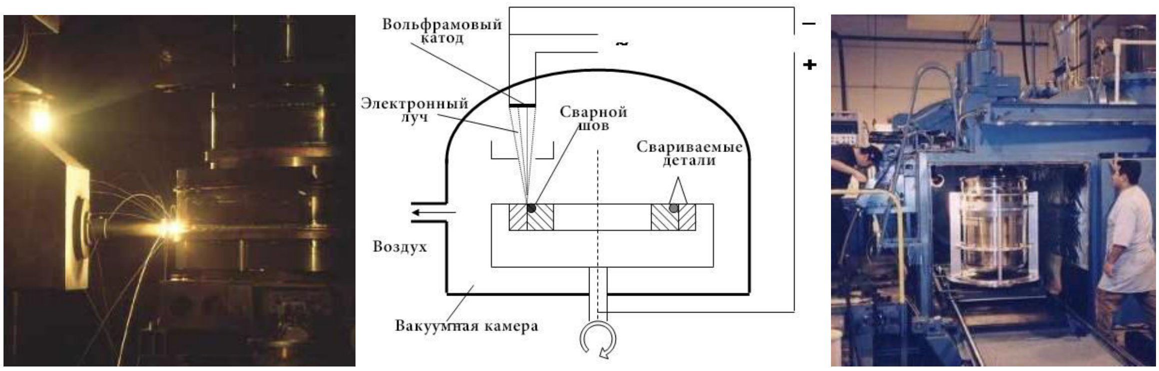


Figure 4. Electron beam welding is performed in a special chamber.

F. Electron beam processing machines

One of the main characteristics of electron beam welding is the principle of operation of its equipment. According to the value of the operating accelerating voltage, the installations are divided into: low voltage (10 kV – 30 kV); average (40 kV - 60 kV); high voltage (100 kV - 300 kV). Among all the options for the used welding equipment can be distinguished specialized and universal installations that work with a pressure of 1 to 10 Pa. According to their design features, three types of electron beam processing machines are distinguished [4]:

- chamber design (Figures 5a, 6);
- execution of a type of work table that work with a certain production rate (Figure 5b);
- transient design (Figure 5c) as well as three types of generators for electron beam control according to their technological purpose:
- for heat treatment (hardening of steels, melting of alloy mixtures);
- for processing during assembly (welding and soldering);
- for processing by metal removal (drilling, perforation, engraving).

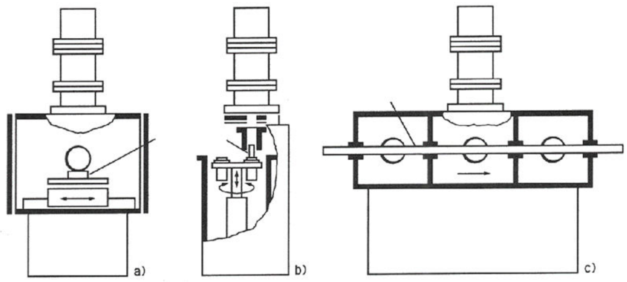


Figure 5. Types of electron beam processing machines.

Figure 6. Electron beam welding chamber[3].

Universal chamber machines are used for processing single parts and those in small batches. For large batches, as well as for larger parts, worktop machines are most often used. For the preparation of blanks and semi-finished products are best suited machines. Machinery companies can be seen, for example, in 3.

III. Conclusion

A historical overview is given, the physical foundations of electron beam technology, the types of processing and the state of technology, the development and potential of equipment and application in practice are considered. The advantages and disadvantages are analyzed and the main conclusion is made that the main parameters determine the mode and quality of work and include: Accelerating voltage; Amount of current in the emitted beam; Speed of movement of the beam on the surface of the welded part; Beam focusing accuracy; Duration of pauses and impulses; Degree of vacuum. Despite its complexity and high cost, electron beam welding provides high quality and sufficient penetration depth, which is unattainable for other methods.

References

[1] DR Patent Nr. 188466, Pirani, Anlage zum Schmelzen von Werkstoffen im Hochvakuum durch Elektronenstrahlbeschuss.

[2] DR Patent Nr. 712434, Borries, Elektronenoptische Lochbohrgerät.

[3] Steigerwald, Termobearbeitung durch Elektronenstrahl, Jena, 1953.

[4] König W., Fertigungsverfahren, Band 3, VDI Verlag, Düsseldorf, 1990.

[5] Donges A., Physikalische Grundlagen der Lasertechnik, Hüting Verlag, Heidelberg, 1988.

[6] Материали от семинара "Elektronenstrahl Schweissen, TA Esslingen, 1998.

[7] Кънтунов С. Състояние, развитие, потенциал и приложение на лазерната литография в микро- и наномехатрониката, Созопол, XXX МНТК “АДП – 2021, Издателство на ТУ София, Автоматизация на инж. производство, бр. 3/03.21, ISSN 2682-9584, стр. 4-8.

[8] Кънтунов С., Технологични основи в мехатрониката, микро- и наносистемната техника, Габрово, УИ „В.Априлов”, 2012 година, ISBN 978-954-683-482-9, с.383, COBISS.BG-ID – 1259450340.

[9] Кънтунов С., Техника и технологии за обработване на отпадъци, Габрово, УИ “В. Априлов”, 2014, ISBN 978-954-683-512-3, COBISS.BG-ID – 1268363492

Websites

[10] 1. http://bg.swewe.net/word_show.htm/

[11] 2.https://mmu2.uctm.edu › obrazovatelni-materiali, Кожухаров, електронно-лъчеви техники

[12] 3. https://deltacrp.ru/bg/radial-welding-electron-beam-welding.html

[13] 4. https://bg.hrvwiki.net/wiki/Electron-beam_processing

[14] 5. http://m.bg.ikstechnology.com/info/electron-beam-processing-principle-42679304.html

[15] 6. https://bgdepe.ru/remont/31256-elektrofizichni-metodi-na-metaloobrabotka.html

[16] 7. https://bg.malayalamwiki.com/413134-electron-beam-welding-PCYDXNM. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.