Electron beam welding pdf

M.St. Weglowski, ... A. Phillips, in Welding and Joining of Aerospace Materials (Second Edition), 2012Electron beam welding processes are usually carried out in a vacuum, yet there are also nonvacuum welding machines available. Modern electron beam welding machines 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 maximize the operator's protection against radiation and carry out technological processes in the vacuum [43]. The division of electron beam welding machines is shown in Fig. 6.10. Types of electron beam welding machines due to working chamber design are shown in Fig. 6.11. The example of a universal and specialist electron beam welding machine for welding are shown in Figs. 6.12 and 6.13, respectively. Due to technological, production-related and metallurgical requirements electron beam welding solutions include the following machines [19]:Fig. 6.10. Division of electron beam welding machines [43].Fig. 6.11. Types of electron beam welding machines due to working chamber design (A) universal welding machine with chamber, (B) cycle machine, (C) continuous operation welding machine (lock).Fig. 6.12. A universal electron beam welding machine model XW150:30/756 for welding and surface modification installed at the Institute of Welding in the year of 2014, (30 kW, 150 kV), produced by Cambridge Vacuum Engineering (CVE).Fig. 6.13. Example of a specialist electron beam welding machine for welding subsea pipelines.–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 minimizes the time needed to generate the vacuum;–nonvacuum 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 toward 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-efficiency pumps and special electron beam discharge orifices to ensure the highest vacuum decrease gradient between the electron gun and atmosphere.Electron beam welding machines—irrespective of their size, intended use and manufacturer—are composed of [7]:–an evacuable working chamber,–located inside it, a movement system for the workpiece (if necessary, for the generator as well),–the working chamber pumping unit,–the EB generator,–the EB generator pumping unit,–the high voltage supply, grid and filament supply,–the machine controller (frequently with an interface to higher-level systems),–a cooling system for the power components,–a compressed air system for certain tooling and valve movements.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 [44]:–automatic beam alignment system,–electron-optical monitoring system,–automatic seam tracking,–control of the process,–fast deflection generator,–wire as well as powder feeder.To achieve narrow weld and deep penetration, it is essential to focus the beam on the workpiece very accurately. However, the focus position of the electron beam is dependent on various parameters as well as the accuracy of the gun assembly. The electron beam focus is typically achieved by controlling the accelerating voltage, beam current, focus coil current, vacuum levels in the gun and in the chamber, and the working distance. These parameters finally control the beam power density. Therefore, these parameters are tightly controlled in the welding process. It should be underlined that the erosion of cathode over time, changes in the alignment of various magnetic lenses, etc. may also cause variations in beam characteristic. The surface focus of the beam at low beam current levels is usually checked by machine operators prior to carrying out welding. Elmer [45] pointed out that this could substantially vary from operator to operator and from machine to machine. This observation was also reported by Giedt and Tallerico [46] where they found that there may be ± 20% to ± 40% variations in the weld depth just due to manual focus adjustment by different operators. Hence, the independent measuring beam characteristics like beam current, beam current density distribution, beam-width, beam brightness system become more popular in industry (Fig. 6.14) [47].Fig. 6.14. Electron beam quality control device Beam Probe by CVE and TWI.C. Selcuk, in Advances in Powder Metallurgy, 2013EB welding is normally carried out in high vacuum (e.g. 10–6 mbar). Therefore it is a batch process and may be expensive and thus restricted to high value parts only. It has a tendency to give high cooling rates and high hardness in C-steels, similar to laser welding, but is likely to have a greater tendency towards pore formation as the vacuum encourages trapped gas to try to escape during welding. It is reported that porosity increased with reduced travel speed. However, it has been demonstrated that weld metal porosity content in sintered ferrous compacts with a range of porosities can be controlled by beam parameters10 and a non-vacuum EB welding process has been used for sintered parts.11Any residual films, such as heat treatment quench oil trapped in the pores of a PM part, were found to have a detrimental effect on EB welding.12 A fine grain size (< ASTM 8–9) in a sintered PM part was reported to be essential for good EB weldability, presumably due to improved ductility, in high temperature PM superalloys.13 This is related to increased ductility and toughness of a fine grained material for absorbing strains upon solidification. Cracking has been observed in EB welding of PM superalloys designed for aerospace applications (engine components such as turbine discs) which required further investigation.14 However, despite the problems described above, EB welding has the ability to give low distortion, again similar to laser welding, or at least uniform distortion effects, which is important for preserving the dimensional stability of near net shape PM components (Fig. 13.5).13.5. Example of (a) EB welding configuration with reduced pressure and (b) reduced pressure EB welds in C-Mn steel(courtesy of TWI Ltd). Dipl.-Ing.H. Schultz, in Electron Beam Welding, 1993Electron beam welding, with few exceptions, is carried out in a vacuum. The vacuum intensifies the degassing process mentioned, which occurs during the liquid and vapour phases. In general this improves the properties of the material concerned, which is why vacuum degassing of certain metals is widely practised in industry. The electron beam welding process is, however, not the most suitable means of improving the fusion zone of a metal by vacuum refining. On the one hand, in the case of certain special steel, nickel and cobalt alloys, vacuum melting is a requirement in their manufacture to ensure porosity and crack free electron beam welding. In these cases, the vacuum effect occurring during welding is insufficient to permit adequate degassing during the short liquid and vapour phases. On the other hand, certain aluminium and copper materials contain high vapour pressure alloying additions such as magnesium and zinc. These escape in such large quantities during electron beam welding that the previously mentioned beam de-focussing is, for technical reasons, insufficient to prevent the process of degassing.A particular aspect of the vacuum effect to which relatively little attention is paid must also be mentioned. As is generally known from welding with tungsten electrodes under a shielding gas, addition of 1–3% oxygen to the argon significantly reduces the surface tension of the weld pool. This effect is also noticed in electron beam welding, where the complete absence of oxygen causes the weld pool to become very viscous and, together with violent motion within the weld pool and high rates of cooling, causes undercutting and very distinct scalloping of the crown of the weld on solidification (Fig. 78).Fig. 78. Crown of an electron beam weld showing scalloping (8: 1, Reproduced: 0.6 X).E. van Walle, in Encyclopedia of Materials: Science and Technology, 2001EBW is the most versatile reconstitution technique but, along with laser welding, the most expensive. EBW can in principle be applied to all kinds of geometry. The electron beam with energy densities up to 108 Wcm−2 allows deep penetration and creates homogeneous, narrow V-shaped welds and small heat-affected zones (HAZs). Small weld widths and HAZs are important in small insert applications. In most situations the components are welded together without additional finishing requirements. However, by preference, the specimens should be welded from both sides—each time to half the thickness of the material—to avoid bending the specimen. Since EBW is performed in a vacuum chamber, hot-cell application (see Hot Cells, Glove Boxes, and Shielded Facilities) is tedious and needs a lot of space. Precautions, also due to the vacuum conditions, must be taken to keep the insert temperature low enough during and after the welding: a cooled sample-clamping system and a time gap between the two reconstitution welds are necessities (Klausnitzer and Hofmann 1992).T. Álvarez Tejedor, ... P. Pilidis, in Modern Gas Turbine Systems, 2013 EBW is a high-energy density fusion process that is accomplished by bombarding the joint to be welded with an intense (strongly focused) beam of electrons that have been accelerated up to velocities 0.3–0.7 times the speed of light. The instantaneous conversion of the kinetic energy of these electrons into thermal energy as they impact and penetrate into the work piece on which they are impinging causes the weld-seam interface surfaces to melt and produces the weld-joint coalescence desired. EBW is used to weld any metal that can be arc welded; weld quality in most metals is equal to or superior to that produced by GTAW.22 The main advantages are:•It can make deeper and more narrow welds than any other process.•High speeds and high production rates.•Good energy conversion efficiency ~65%. For production applications is cheaper to operate than LBW.However the first cost is high. Because of the small beam, joints and tooling must be precise.In Duplex Stainless Steels, 1997Electron beam welding (EBW) is especially suited to producing joints of heavy section materials (around 50 mm) in one or two passes. It tends to produce rapid cooling rates and therefore highly ferrite in the melt zone (91% ferrite in S31803),32 particularly in thin sections. Nevertheless, the toughness remains high which can be attributed to the very low oxygen content in the weld. About 20% of the base metal nitrogen content is lost33 and so with highly alloyed grades, it may be possible to design base metals for autogenous EBW, although this does not appear to have been done to date.Other work has examined the use of filler additions using 0.15 mm thick 309-type or pure nickel SAW strips.34 By varying the amount of strip added, satisfactory phase balances have been achieved in 50 mm thick S31803 and S32760 plates. The corrosion and mechanical properties recorded for the S31803 joint were found to be comparable to fusion joints.Klas Weman, in Welding Processes Handbook (Second Edition), 2012Electron beam welding uses a very high-energy electron beam to produce deep, narrow penetration. The electron beam has a higher energy content than a laser beam, and is also smaller. Penetration is deeper for a given level of power, and the overall efficiency of the energy conversion process from input electricity to output beam power is much higher. Important characteristics include the high energy density, which makes it possible to melt the gap between two parts without the problem of distortion.Welding normally has to be performed in a vacuum as the electron beam is absorbed by air. This complicates the process when changing the workpiece. On the other hand, the absence of air is good for the welding process, as there are no reactions between the air and the metal of the weld or the workpiece. Welds are normally made as butt welds.Electron beam welding is often used for advanced materials and complex, critical parts such as turbine rotors, but it can also be suitable and economic for many simpler processes involving large production runs. It is very suitable for butt welding materials of different thicknesses, but is particularly competitive for welding thick materials of up to 250 mm. Electron beam welding has the following advantages:•The high flexibility of this method permits everything from thin sheet to very thick materials to be welded.•Welding speed is much higher than (for example) arc welding. However, when assessing overall productivity, allowance must be made for the time required to evacuate the air from the vacuum chamber.•The vacuum means that reactive materials such as titanium can be welded without risk of oxidation.•Welds are narrow, with a high penetration/depth ratio.•Heat input is low in absolute terms, resulting in low residual stresses and little distortion of the workpiece. Reproducibility and tolerances are also good, as the method is mechanised.•Many otherwise difficult materials and material combinations can be welded.•The method is perfect for sealing vacuum chambers.It may be necessary to demagnetise magnetic materials before welding them, as the magnetic field could otherwise deflect the electron beam. Joint preparation must be carried out carefully, including ensuring accurate positioning. Careful control of the beam track along the joint is also essential.The electron gun (see Figure 12.6), is supplied from a high-voltage power source (30–175 kV), but at a low current (less than 1 A). The electrons are accelerated from the anode and are focused and deflected by magnetic coils in a manner similar to that used in television and computer screens.Figure 12.6. Electron beam welding.The electron beam requires a vacuum, and so welding is carried out in a vacuum chamber. This normally requires the chamber to be opened to load or change a work-piece, after which the air must be evacuated by a high-vacuum pump. However, various designs that use forms of air locks for the loading and unloading of materials have been developed to deal with smaller items or (for example) strip materials. When the electron beam meets the workpiece, it produces a secondary emission of x-rays, and so the vacuum chamber also provides protection against this radiation.Although the electron gun itself requires a high vacuum, the vacuum in the rest of the chamber does not need to be quite so high. The electron beam can even travel a short distance in air, but is quickly absorbed and scattered, so limiting penetration. In addition, if the welding is performed outside the vacuum chamber, some other method of protection against x-rays will be required.Welding is normally performed by traversing or rotating the workpiece by programmable control, with the electron beam remaining stationary. Particular attention must be paid to maintaining appropriate accuracy, bearing in mind the narrow beam and joint. However, this can be achieved by deflecting the beam to make it sweep back and forth across the joint (though this affects the penetration profile) or by joint tracking.Ramesh Singh, in Applied Welding Engineering, 2012Electron beam welding (EBW) is another focused beam welding process. The process develops energy by bombarding the work-piece with a focused beam of high velocity electrons. The power density (PD) defines the process's ability to develop enough heat for welding. The PD in Watts per unit area is obtained by the following equation:Where:n=total number of electrons per second in the beame=the charge on an individual electron (1.6×10−19 coulombs)E=the accelerating voltage on the electrons, V, in voltsI=the beam current, in amperesA=the area of the focused beam at the work-piece surfaceThe beam current, accelerating voltage and welding speed are the factors that determine the depth of penetration of a focused beam.The power concentration of 1 to 100 kW/mm2 is routinely achieved, and up to 10 MW/mm2 can be obtained for most welding. The concentration of energy is dependent on accelerating voltage. Electron beam welding is generally performed at voltages between 20 kV to 150 kV; a higher voltage corresponds to a higher power density.The EBW process has several advantages due to its focused heat source for welding, as listed below:1.Welds with higher depth to width ratio can be successfully achieved.2.High strength of weld can be achieved.3.Ability to weld thick sections in a single pass.4.The relative low heat input results in low distortions in the base metal.5.Very narrow HAZ.The welding process involves the application of high power density, which instantly volatizes the metal. This creates a needle-like, vapor-filled cavity or keyhole in the work-piece, which allows the beam to penetrate through the section of the metal to be welded. The cavity is kept open by the pressure of the vapor. The flow of the molten metal is from the front to rear of the keyhole, as the weld solidifies.Three commercial variants of the EBW process are given Table 2-2-2.Table 2-2-2. EBW VariantsEBW Variant DescriptionOperating Pressure1High Vacuum EBWA pioneer process13 MPa (10−4 torr) or lower2Medium Vacuum EBWSoft vacuum processAt 13 MPa (10−4 torr)3Nonvacuum EBWAt 100 kPa (1 atm) Dipl.-Ing.H. Schultz, in Electron Beam Welding, 1993Electron beam welding machines not only differ in their maximum beam power, but also in the dimensions of their working chambers and the way in which the workpiece is moved. For example, universal welding machines, as has already been mentioned, are equipped with working chambers of different standard sizes of 0.5–40m3 depending upon the purpose for which they are to be employed (Fig. 221 and 222). The load carrying capacity of the working table and, if used, the rotary positioning arrangement is designed according to the volume of the working chamber, which governs the maximum weight of workpiece which can be accepted (Fig. 223). Universal machines generally have an optical viewing system, manifold beam controls and powerful pumps to evacuate the larger working chambers rapidly. To add to the flexibility of these machines, the electron beam gun can generally be mounted on the working chamber in a number of positions (Fig. 72).Fig. 221. Electron beam welding machine for welding various types of small component. P = 3 kW,V = 0.6 m3.Fig. 222. Production electron beam welding machine for manufacturing gas turbine rotors. P = 30 kW,V = 20 m3.Fig. 223. Electron beam welding machine for welding in the aerospace industry. P = 2 × 30 kW, V = 18 m3.For welding small series of turned components in universal machines a multiworkpiece positioning arrangement is used, in order to weld the greatest possible number of workpieces in a single evacuating cycle (Fig. 224).Fig. 224. Multicomponent positioning system for welding small series of rotating components.Large numbers of turned components, such as toothed gear wheels in the gearbox manufacturing sector of the automobile industry, are welded on cycle type machines. The particular characteristics of these types of machine are their small working chambers, which can accept only one or at most a few workpieces together with their clamping jigs at any one time. These machines have working chambers with volumes of 1–20 litres which makes it possible to evacuate them in only a few seconds (Fig. 225). In the case of cycle machines no optical viewing system is necessary and the operating console will only have switches to turn the machine on and off, an emergency off switch and a number of indicator lamps to monitor (Fig. 226 and 227). The entire working sequence, from evacuating, rotating the workpiece, welding and changing the workpiece is all carried out automatically according to a predetermined program and with a high degree of reproducibility of the set welding parameters. In incorporating such machines into transfer production lines, special additional pieces of equipment automatically transport the workpieces to the point of welding and move them on once this operation has been completed (Fig. 228).Fig. 225. A production line welding machine.Fig. 226. A cycle type machine for welding gear components for the automotive industry.Fig. 227. A production line machine for welding parts for the measuring and control industry.Fig. 228. An arrangement for automatically feeding a production line welding machine for toothed gear wheels.Continuous welding machines, representing another type of electron beam welding machine, are mainly used to manufacture bimetallic semi-finished products such as bandsaw blades, thermo-bimetallic materials, electrical contacts, etc.The workpiece is fed into the working chamber in the form of an endless band of material through a special arrangement of vacuum locks, where it is continuously welded and then transported through further locks out of the machine (Fig. 229). Depending upon the dimensions of the band, welding is carried out at speeds up to 330 mm s− 1 = 20 m min− 1. This puts a severe requirement on the dimensional tolerances of the workpiece as well as on the constancy of the welding parameters. For continuous welding of bimetallic strip a row of other work stations is connected to the continuous welding machine (Fig. 230). Amongst these are a butt welding machine to join the strips end to end to form an endless coil, together with various types of cleaning plant, numerous types of measuring and monitoring arrangements and, for example, for band saw blading, an induction furnace for stress relief annealing of the strip prior to mechanical working (Fig. 231). There is more on bimetallic band saw blading in section 10.4.Fig. 229. Construction of a continuous machine for welding strip material.Fig. 230. A complete installation for continuous welding of bimetallic band saw blading material [142], 1 Reel of unwelded strip; 2 Machine for flash butt welding the ends of the strip; 3 Strip storage hopper; 4 Degreasing plant; 5 Washing and drying plant; 6 Electron beam welding machine; 7 Strip counting unit; 8 Stress free annealing stage; 9 Take up reel for the welded bimetallic strip.Fig. 231. Part of a machine for welding bimetallic band saw blading material.Other continuous welding machines operate with pressure stage airlock systems and are suitable for individual workpieces, mostly turned items with small dimensions (Fig. 232). The workpieces are fed into the working chamber through long airlock tubes and after welding are brought out of the chamber through a similar system into the surrounding atmosphere. A well known example of this is the electron beam welding of pre-ignition chambers for diesel motors (see section 10.2).Fig. 232. Electron beam welding machine with pressure stage airlocks for welding precombustion chambers for diesel motors. Dipl.-Ing.H. Schultz, in Electron Beam Welding, 1993Electron beam welding with a filler wire has been pursued for many years with the aim of joining poorly machined faces with varying or large weld gaps.Successful though the initial laboratory trials were [116-118116117118], it was shown that irregularly varying weld gaps required use of automatic wire speed control. With the advent of beam powers of over 7.5 kW, not only could thicker walled material be welded but also larger components with normal dimensional tolerances, using a mobile vacuum system. Automatic wire speed control played a particularly important role in development of this type of welding [119]. The problem of automatic wire speed control was solved by extremely rapidly sensing the unwelded weld gap using the deflected, and thus somewhat advanced, full power electron beam. At the same time, variations in the X-rays generated as the beam traverses across the weld gap are measured (Fig. 141). The position of the weld gap in relation to the electron beam and the width of the gap can thus be sensed by an X-ray detector and turned into a measurement signal which can be used to control the speed of the filler wire. The instrumentation required for this type of welding, which also incorporates a number of other control and monitoring processes, is considerable and only economically justifiable when components are to be welded which, because of their size and weight, cannot be guaranteed to maintain a specified weld gap tolerance during assembly and welding. In all other cases the more normal machining of the faces of the joint is considerably more cost-effective, and for numerous electron beam welded finish machined workpieces entails no additional work above that required to ensure dimensional accuracy.Fig. 141. Radiographic method of measurement for controlling the speed of filler wire feed in welding joints with varying weld gap width.This type of welding can be used for a different purpose, however, as for example in the case of arc welding, if the faces of the joint are machined to a V or Y shaped preparation and the void left must be made up using a filler metal (Fig. 142). This type of process offers the possibility of joining components with large wall thicknesses when the beam power available is otherwise insufficient to penetrate the full thickness of the material in the conventional way in a single pass [120, 121]. Figure 143 shows schematically the arrangement of electron beam and wire feed used in the case of a V weld. It must not, however, be forgotten that a large number of additional parameters such as the speed, positioning and angle, etc, of the wire must also be taken into account. There are particular advantages to be had in using a Y shaped preparation, including a stepped increase in the width of the gap (Fig. 142, below, right). As a result of the increase in width of the gap towards the top, significantly less angular shrinkage takes place and the effective preheat applied using a multipass technique (Fig. 144) results in an overall decrease in hardness (Fig. 145). Welding can also be carried out using two wires to increase the rate of melting [122]. Thus, summarising, in all cases the increased cost of electron beam welding with filler is considerable and only appears justified when there is limited beam power, large wall thicknesses are to be welded and no other solution is possible.Fig. 142. Various ways of preparing the workpiece when electron beam welding thick plate materials using a multipass technique.Fig. 143. Electron beam welding with one and two filler wires respectively.Fig. 144. Cross section through a 6-pass electron beam weld, plate thickness: 100 mm, Y weld preparation with settings UB = 140 kV, IS = 40 mA. 1. Layer: Without filler material; 2. to 6. Layer with 0.8 mm thick weld filler wire [120].Fig. 145. Hardness profile through the depth of an electron beam weld produced using filler material, plate thickness: 60 mm, Y weld preparation with step. Parent metal St 52–3. Filler material identical, 0.8 mm thick [120].