HIGH ENERGY DENSITY WELDING PROCESSES

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Contents

Summary

Occurring late in the manufacturing stream, the joining process is typically the final step in assembly and plays the major role in ensuring structural performance. Additionally, the emergence of near-net-shape processes to produce sub-components has raised the importance of assembly processes as the next area for increased production efficiency. To solve all the joining needs that require welding, many different processes have been developed along the years. Two of welding technologies can be classified as High Energy Density Welding (HEDW) processes because of their working characteristics. These technologies are Laser Beam Welding (LBW) and Electron Beam Welding (EBW). Both are capable of proving extremely high-power-density weld input levels and making deep weld penetration possible. LBW and EBW are quite similar, differing most notably in their source of power. Laser beam welding employs a highly focused laser beam, while electron beam welding uses an electron beam. LBW and EBW have been developed rapidly and have been successfully used in many industrial applications; the potential of the HEDW process is continuously being exploited in further industrial sectors. This chapter presents description of the fundamental principle of work of both EBW and LBW. Equipment, process parameters, control of energy, weld formation and typical joint designs are described

1. Introduction

Welding is a precise and reliable joining process that produces a local coalescence of materials. This is often done by local melting the workpieces and adding a filler material to form a pool of molten material that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. In essence, the welding process fuses the surfaces of two distinct elements to form a single unit. Welding encompasses a broad range of joining techniques that include fusion welding, solid state welding, weldbonding, diffusion welding, brazing, and soldering. Various techniques allow a great deal of flexibility in the design of components to be welded. Welding technologies also include methods for welding metals, dissimilar metals, polymers, and ceramics, as well as emerging composite and engineered materials.

2. High Energy Density Welding Processes

High energy density welding is every fusion welding process utilizing a heat source capable of proving extremely high-power-density weld input levels. The density of the energy available from a heat source for welding is often more important than the absolute source energy. Two major types of high energy density welding processes are Electron Beam Welding, and Laser Beam Welding. Both processes use a very high-intensity beam as the heating source for welding, one in which the energy from the source is highly concentrated by electromagnetic or optical lenses, respectively. The energy density in these processes is approximately 10^{10}–10^{13} W/m^2. Typical arc welding processes have energy density of about 5 x10^8 W/m^2. Conversion of the kinetic energy of fast-moving electrons in EBW and photons in LBW into heat occurs as these particles strike the workpiece, leading to heating, melting, and vaporization in a highly localized area. Both processes usually operate in the keyhole mode. Penetration into workpiece can be high, producing deep, narrow, parallel-sided fusion welds with narrow heat-affected zones and minimal angular distortion due to non-uniform weld metal shrinkage or thermal contraction. The Electron Beam Welding process is almost always performed autogenously, so joint fit must be excellent. If filler is needed for thick section welds, pre-placed shims must usually be used, as getting wire down into a deep weld is difficult. Laser Beam Welding is usually done autogenously also, but can use wires as a filler. Shielding for the EBW process is provided by the vacuum (typically 10^{-3}-10^{-5} atmospheres) required to allow the beam of electrons to flow to the workpiece unimpeded by collisions with molecules comprising air. Shielding for the LBW process is accomplished with inert gases, gas mixtures or in so-called ‘‘dry-boxes’’ or from special shrouds over the vicinity of the weld puddle.

These two processes are compared in Table 1.

ELECTRON BEAM WELDING	LASER BEAM WELDING
Deep penetration in all materials	Deep penetration in laser-absorbent materials
Very narrow welds, high depth/width ratio	
High energy density; low heat input	
Capable of very high welding speeds	
Needs vacuum to operate unimpeded	Can operate in air, inert gas, or vacuum
Requires tight fitting joints	
Almost impossible to add filler	Filler can be added at lower penetration welds
Capital equipment is expensive	
Very high electrical efficiency (99%)	Very low electrical efficiency (<15%)
Needs backup beam absorption	Rarely needs backup beam absorption
Generates x-rays from workpiece	No x-ray generation

Table 1. Comparative Advantages and Disadvantages of the EBW and LBW Processes

3. Basic Principle of Electron Beam Welding

Electron Beam Welding is a fusion welding process in which a beam of high-velocity electrons is applied to the materials being joined. The kinetic energy of the electrons is transformed into heat upon impact on surface of the working material. The workpiece and the filler metal, if used, melts to form a part of the weld. The welding is often done in conditions of a vacuum to prevent dispersion of the electron beam.

As the electrons strike the workpiece, their energy is converted into heat, instantly vaporizing the metal under temperatures near 25,000 °C. The heat penetrates deeply, making it possible to weld much thicker workpieces than is possible with most other welding processes. However, because the electron beam is tightly focused, the total heat input is actually much lower than that of any arc welding process. As a result, the effect of welding on the surrounding material is minimal, and the heat-affected zone is small. Distortion is slight, and the workpiece cools rapidly, and while normally an advantage, this can lead to cracking in high-carbon steel.

Almost all metals can be welded with electron beam welding technology, but the most commonly welded are stainless steels, superalloys, and reactive and refractory metals. Due to special features of this process, e.g., high energy density and accurately controllable beam size and location, in many cases it has proven to be an efficient way of joining dissimilar metals. Electron Beam Welding process is not limited or controlled by thermal conduction. This enables welding of metals with high thermal conductivity, or joint designs with asymmetric heat transfer characteristics. EBW is a very similar process to Laser Beam Welding, except that electrons are focused in electron beam instead of photons in the case of lasers beam. The advantage of using an electron beam is that the beam does not have a tendency to diverge as laser beams do when they contact the workpiece.

3.1. Formation of an Electron Beam

Electron beam processing can be performed both in and out of vacuum utilizing fixed or mobile guns, high or low voltage, etc. An EBW system typically includes the following subsystems: electron beam gun column, high-voltage power supply, vacuum pumping, motion control, and welding enclosure. Two additional subsystems available on many machines are seam tracking and programmable system controls. Electron beam gun column allows the electron beam welding machine to produce free electrons, from these electrons into a concentrate high-power beam, and direct the electron beam through space. Electrons are generated in a vacuum enclosure by heating the cathode made of tungsten, a negatively charged emitter, to its thermionic emission temperature causing electrons to “boil off” of the filament. As the temperature is increased, more electrons are emitted from the cathode until a maximum emission level is reached. This level, called space charge limited emission, occurs when a cloud of electrons is formed that repels further emission from the filament. In a triode gun this cloud of electrons is shaped into a beam by an electrostatic field created by an appropriately shaped and charged bias cup and a positively charged anode. The combination of all three of these components constitutes an electron beam gun, Figure 1 presents a simplified scheme of an Electron Beam Gun.

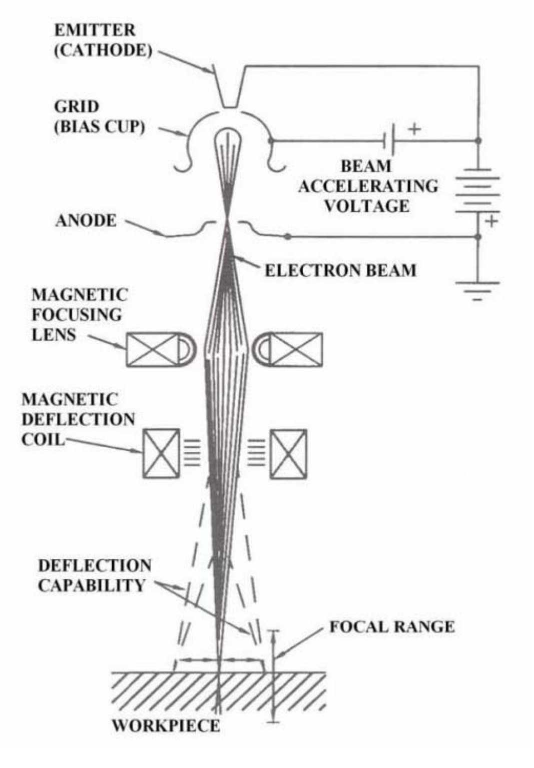

Figure 1. Simplified scheme of an Electron Beam Gun

In a diode gun, the bias cup and the emitter are at the same electrical potential and are referred to as the cathode. In a triode gun, the cathode is at one potential while the potential (bias) between it and the bias cup is varied to control the beam current. At a large negative bias, electron flow is inhibited, and the beam current is zero. As the value of the negative bias is reduced, electron flow increases. In both gun designs, electrons are accelerated to a hollow anode (which is at ground potential) inside the gun column by means of a high voltage differential. They pass through the anode at high speed (approximately half of the speed of light) and then are directed to the workpiece with magnetic forces resulting from focusing and deflection coils. All of these components are housed in an electron beam gun column, in which a high vacuum is maintained. The difference between a diode and triode gun is that beam current and beam voltage can be independently varied (within limits) with a triode gun.

3.2. Control of the Electron Beam

Since electrons are charged particles, their direction of travel can be controlled by the use of electromagnetic fields. The electron optics segment of the column assembly is comprised of a focus coil and a set of deflection coils that serve to constrict the electron beam to a tightly concentrated focal spot and deflect the beam over the workpiece surface. When the accelerated beam of electrons emerges from the aperture in the anode and begins to diverge (because of mutual repulsion and other causes) a focusing coil located below the anode can be used to counteract this divergence. By simply varying the current applied through this coil the electron beam can be focused at the desired location beyond the plane of the coil. Deflection coils can be added below the focus coil to cause the beam to move to predetermined locations. Modern welding systems usually include a function generator or a programmable deflection module to power deflection coils, thus providing a versatile means of controlling beam movement.

3.3. Weld Formation

The high energy density of the focused beam vaporizes some of the material on which it is directed. A keyhole forms in a steady state condition between the pressure of this expanding vapor and the surface tension of the molten material on the wall. As the beam traverses over the base metal the material melts at the leading edge of the keyhole, flows around the keyhole, and solidifies at the trailing edge. The formation of the keyhole in high power density EBW provides the unique capability for deep, narrow welds and narrow heat–affected zones resulting in minimized distortion of weldments. This type of melting is referred to as keyhole mode welding. In contrast, lower energy density beam spots results in wider, shallower welds with aspect ratios typical of arc welds. This latter mode of energy transfer is called the conduction mode.

3.4. Welding Variables

In EBW, the primary welding parameters are beam voltage, beam current, travel speed and focus coil current. The secondary variables are vacuum level, distance from gun to work, and oscillation of the beam spot. The amount of heat input, and thus the penetration, depends on several variables, most notably the number and speed of electrons impacting the workpiece, the diameter of the electron beam, and the travel speed. Greater beam current causes an increase in heat input and penetration, while higher travel speed decreases the amount of heat input and reduces penetration. Figure 2 presents shapes and dimensions of melted zones in stainless steel at different values of beam power.

The diameter of the beam can be varied by moving the focal point with respect to the workpiece. Focusing the beam below the surface increases the penetration, while placing the focal point above the surface increases the width of the weld.

The energy conversion efficiency of electron beam welding is higher than that for arc and laser beam welding process. A lower energy input can be used to give equivalent penetration with EBW than with conventional arc and laser beam welding processes.

Precise control of high power densities is required because of the strong influence they can have on the weld geometry. Thus, variations on parameters can often be traced to differences in power density that occurred even when all measured welding parameters (accelerating voltage, beam current, focus coil current and travel speed) appear to be remaining the same. In critical applications care must be taken to ensure filament installation, chamber pressure, beam deflection and distance from gun to work are maintained constant.

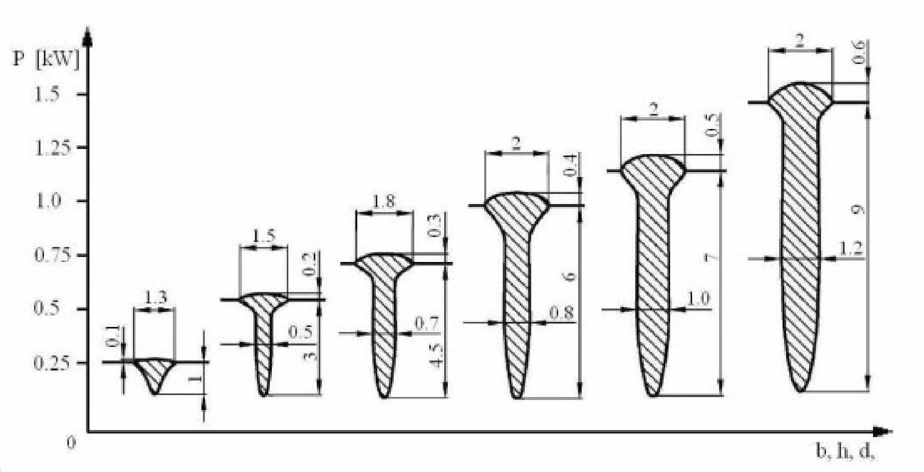

Figure 2. Shapes and dimensions of melted zones in stainless steel at different values of beam power

3.5. Methods of EBW

The three primary methods of EBW are each applied in different welding environments. The method first developed requires that the workpiece in the welding chamber be at a high vacuum approx. 0.133 Pa or lower. Material as thick as 150 mm can be welded, and the distance between the welding gun and workpiece (the *stand-off distance*) can be as great as 0.7 m. While the most efficient of the three modes, disadvantages include the amount of time required to properly evacuate the welding chamber and the cost of the entire machine. As electron beam gun technology advances, it became possible to perform EBW in a soft vacuum, under pressure of 13.3 Pa. This allows for larger welding chambers and reduces the time and equipment required to achieve soft vacuum in the chamber, but reduces the maximum stand-off distance by half and decreases the maximum material thickness to 50 mm. The third EBW mode is called nonvacuum or out-of-vacuum EBW, since it is performed at atmospheric pressure. The stand-off distance must be reduced to 40 mm, and the maximum material thickness is about 50 mm. However, it allows for workpieces of any size to be welded, since the size of the welding chamber is no longer a factor. Highest production rates and lowest costs per part are some of the advantages of nonvacuum EBW since there is no evacuation time involved. The welding atmosphere scatters the beam which results in decreased power density, lower aspect ratio welds compared to those of equivalent power made in vacuum. Figure 3 shows both modes of operation.

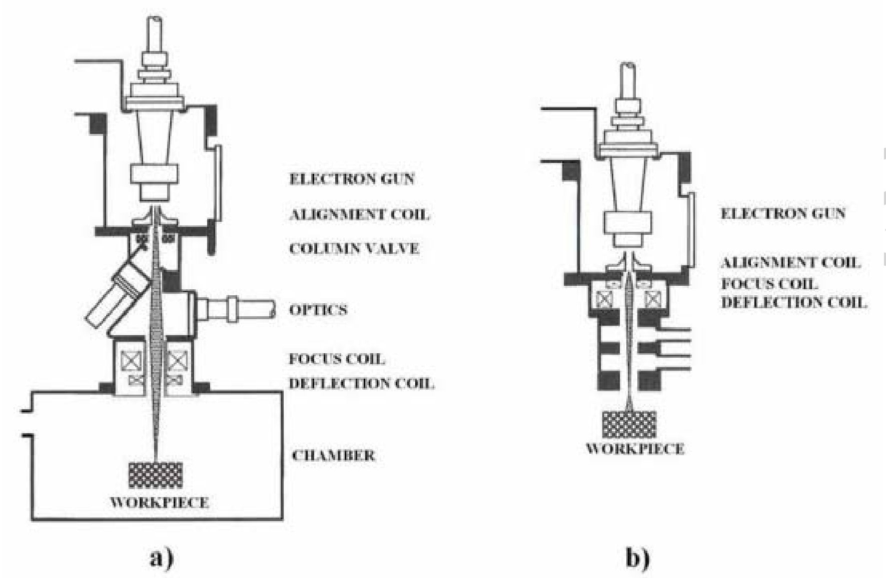

Figure 3. EBW modes of operation: a) EBW at a high vacuum b) EBW at non vacuum

3.6. Description of the Equipment

As mentioned before, Electron Beam Welding can be performed both in and out of vacuum utilizing fixed or mobile guns, high or low beam voltages, etc. The electron beam gun column is the main part of the electron beam welding system. It produces free electrons, form these electrons into a concentrated high-power beam, and direct the electron beam through space.

The electron optics segment of the column assembly is comprised of a focusing coil and a set of deflection coils that serve to constrict the electron beam to a tightly concentrated focal spot and deflect the beam over the workpiece surface.

The high-voltage power supply is housed in an oil-filled tank. The same tank also contains the beam current control and the cathode-heating power supplies. An associated control system serves to maintain the outputs of the power supplies constant regardless of line voltage or load variations. Some variations of power supply incorporate fiber optics for sending and receiving of control signals to achieve fast response times.

EBW machines with high vacuum mode of working have either one or two vacuum pumping systems. Before start of working the gun column and the welding chamber are evacuated together when using one pumping system and separately when using two pumping systems. The latter system is preferred to minimize evacuation time and to maintain a better vacuum in the gun column while welding chamber is vented. For the gun column, only a small capacity auxiliary vacuum pump is required to ensure high-vacuum level. The welding chamber must be airtight and strong enough to prevent it from being crushed by atmospheric pressure. It must have openings so that the workpieces can be inserted and removed, and its size must be sufficient to hold the workpieces but not significantly larger, as larger chambers require more time to evacuate.

Weld motion system ensures either workpiece motion or a combination of gun and workpiece motion to accomplish welding. In order to fuse the entire length of a welded joint, the joint must be advanced under the beam or, conversely, the beam must be advanced along the joint. EBW equipment manufacturers generally offer both fixed (externally mounted) and mobile (internally mounted) gun systems.

Seam-tracking equipment is available for all electron beam welding systems. Some seam trackers work on the principle that electron backscatter, produced by an incident low-power electron beam, is absorbed or randomly scattered by discontinuities on the work surface. If the level of backscatter current is monitored as the beam is scanned, a change will be noted each time when the beam crosses the joint. This technique can be used either prior to, or during the actual welding process.

Modern EBW systems are supplied with programmable logic control of the discrete sequencing functions and welding parameter analog inputs/outputs. A beam-control module serves to turn the beam instantaneously ON/OFF and vary the magnitude of beam current in a ramped or stepped mode. Separate focus and deflection control modules may be installed to intermittently or continuously vary the plane in which the beam focal spot occurs, and may move this beam focal spot about in fixed or oscillatory manner, or both. CNC is optionally provided with software that allows part programs to be entered in conventional CNC machine tool manner.

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Biographical Sketches

Branko Bauer has received his diploma of Engineering (Dipl.Ing.) from the University of Zagreb, Faculty of mechanical engineering and naval architecture, Department of Welded Structures, Chair of Welding, Croatia in 1997. He began to work at the Faculty of mechanical engineering and naval architecture, Zagreb in 1997. He obtained a certificate of European Welding Engineer after completing course according EWF program in 1999. After completing further studies he obtained a Master of Science (M.Sc.) degree in 2002, and he earned a PhD-degree (Dr.sc.) in 2006. At the Welding department of the Faculty he is in charge of research in laser beam welding and cutting. In 2007 he was appointed Assistant professor at the Faculty of mechanical engineering and naval architecture in Zagreb. He has published more than 30 scientific and technical papers.

Matija Bušić has received his diploma of Engineering (Dipl.Ing.) from the University of Zagreb, Faculty of mechanical engineering and naval architecture, Department of Technology, Chair of Machine Tools, Croatia in 2009. He started his first employment in 2009, in the company BAM - ING d.o.o. in Zagreb. After two months he began to work on the Faculty of Mechanical Engineering, University of Zagreb, as an Assistant on the Department of Welded Structures. In academic year 2009/2010 he started postgraduate studies on the Faculty. In his work he participates in academic activities and scientific activities related to laser welding and high energy density welding processes.