

Recommended Practices for Electron Beam Welding and Allied Processes



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American National Standards Institute
February 5, 2013

Recommended Practices for Electron Beam Welding and Allied Processes

4th Edition

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Prepared by the
American Welding Society (AWS) C7 Committee on High Energy Beam Welding and Cutting

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This document presents Recommended Practices for Electron Beam Welding and Allied Processes. It is intended to cover common applications of the process. Processes definitions, safe practices, general process requirements, and inspection criteria are provided.



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Foreword

This foreword is not part of AWS C7.1M/C7.1:2013, *Recommended Practices for Electron Beam Welding and Allied Processes*, but is included for informational purposes only.

Electron beam processing was initiated in the early 1900s, when an electron beam was used to produce tantalum metal by melting tantalum sponge. Since then, electron beam technology for materials processing has steadily advanced and is now commonly used. While electron beam processing encompasses a wide range of metal processing activities, this document focuses on welding and joining. The commercial application of electron beam welding (EBW) was first introduced in the late 1950s and subsequently gained rapid and widespread acceptance by the industrial community because of its ability to produce high aspect ratio (depth-to-width) welds and join dissimilar and difficult-to-weld materials. Welding speeds on the order of 760 mm/s [1800 in/min] and single-pass autogenous welds in metals of greater than 150 mm [6 in] thickness have been achieved.

It has been estimated that there are upwards of 3000 electron beam welders presently in operation throughout the world—of which approximately 35% are involved with automotive related tasks, 15% with both aircraft and aerospace related tasks, 10% with nuclear (either commercial or military) related tasks, 20% with a variety of job shop (contract welding) related tasks, and 20% with other industries (electronic, medical bimetal, Research and Development, etc.). It is also estimated that out of this total number of operating units, approximately 40% of those that were delivered during the '60s and '70s time frame (i.e., units having upwards of 35 years or more of operational time) are still being used on a regular basis—if not by the original purchaser, then by the 2nd or 3rd owner of the unit, thus attesting to the fact that equipment being supplied by the EBW manufactures has a demonstrated history of performing durably and reliably.

The information contained in the Recommended Practices was compiled by the American Welding Society's C7B Subcommittee on Electron Beam Welding and Cutting and has been carefully reviewed by a number of experts in the field, and should provide a helpful guide for use in applying the electron beam welding process. It must be noted that the operating parameters specified in these recommended practices will not be the only possible parameter combinations that can be employed for successfully processing the materials and thicknesses shown. Changes in material composition, dimensional tolerances, and machine calibration will cause changes in the resulting welds. Therefore, the procedures contained herein are offered simply as a guide and are intended only for use in aiding the application of electron beam technology and increasing process consistency.

AWS C7.1M/C7.1:2013, *Recommended Practices for Electron Beam Welding and Allied Processes*, is the third revision (4th edition) of the document issued initially in 1992. This edition adds three new practical examples and adaptations of the electron beam process, including electron beam braze welding (EBBW), electron beam cutting (EBC) and drilling, the deposition of supplementary weld metal (surfacing, cladding, and hard-facing), electron beam additive manufacturing (EBAM), surface texturing, and heat treating of components. Previous editions of the document are as follows:

AWS C7.1-92	<i>Recommended Practices for Electron Beam Welding</i>
AWS C7.1:1999	<i>Recommended Practices for Electron Beam Welding</i>
AWS C7.1M/C7.1:2004	<i>Recommended Practices for Electron Beam Welding</i>

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS C7 Committee on High Energy Beam Welding and Cutting, American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

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Recommended Practices for Electron Beam Welding and Allied Processes

1. General Requirements

1.1 Scope. These recommended practices present descriptions of electron beam welding equipment and procedures for welding a wide range of metals and thicknesses; allied processes, to include electron beam braze welding (EBBW), cutting, drilling, surfacing, additive manufacturing, surface texturing, and heat treating, are also discussed. The appropriate terms, definitions, and safety considerations are presented. Information is included on designing for electron beam welding (EBW), welding dissimilar metals and thicknesses, fixturing, specifications, and operator training and qualification. Information regarding the safe practice of electron beam welding and allied processes can be found in Clause 4 of this standard.

Highly technical and detailed descriptions of metallurgy and the physics of the EBW process, though important to the engineer and scientist, were considered beyond the scope of this publication.

1.2 Units of Measurement. This standard makes use of both the International System of Units (SI) and U.S. Customary Units. The latter are shown within brackets ([]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system shall be used independently.

1.3 Safety. Safety issues and concerns are addressed in this standard, although health issues and concerns are beyond the scope of this standard. Some safety considerations are addressed in Clause 4.

Safety and health information is available from the following sources:

American Welding Society:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS Safety and Health Fact Sheets
- (3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

- (1) Material Safety and Data Sheets supplied by materials manufacturers
- (2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The standards listed below contain provisions, which, through reference in this text, constitute mandatory provisions of this AWS standard. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

ANSI documents:¹

ANSI/ASSE Z87.1, *Occupational and Educational Personal Eye and Face Protection Devices* ;

ANSI/HPS N43.3, *For General Radiation Safety—Installations Using Nonmedical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV*;

ANSI Z535.1, *Safety Color Code*;

ANSI Z535.2, *Environmental and Facility Safety Signs*;

ANSI Z535.5, *Accident Prevention Tags*.

AVS documents:²

AVS M-1, *Vacuum Hazards Manual*.

AWS documents:³

AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*;

AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination* .

3. Terms and Definitions

For the purposes of this document, the following terms and definitions apply:

accelerating potential. See **beam voltage**.

alignment. Any mechanical or electromagnetic adjustment of the electron beam equipment that is made for the purpose of correcting the path or position of the beam.

alignment coils. Electromagnetic deflection coils immediately below the anode used to deflect the beam so its axis coincides with the magnetic axis of the focus coil.

anode. The more electrically positive element of the electron beam gun (usually at the ground potential of the machine) through which the electron beam passes.

back-up bars. Material intended only to stop beam energy exiting the workpiece in full penetration welds.

beam current. Measure of the quantity of electrons flowing per unit time in an electron beam, usually expressed in units of milliamperes (mA).

beam deflection. The position of the beam spot on the workpiece is moved rapidly by small amounts, deflecting the beam back and forth. This oscillatory movement is superimposed on the steady movement along the weld path. The frequency of these oscillations can be from 10 Hz to 10 kHz, in one plane or in a circular, elliptical, or other pattern.

beam deflection coils. Electromagnetic coils used to change the path of the electron beam.

beam forming electrode. See **bias cup**.

beam modulation. Any change in beam current (may be periodic).

¹ ANSI standards are published by the American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

² AVS documents are published by the American Vacuum Society, 125 Maiden Lane, 15th Floor, New York, NY 10038.

³ AWS documents are published by the American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

beam oscillation. See **beam deflection**.

beam power. A measure of the kinetic energy of the beam per unit time and equal to the product of the beam voltage times the beam current. In equation form, the beam power, P , in watts (W), is

$$P = V \times I \quad (\text{Eq. 1})$$

where

V = Beam Voltage, kilovolts (kV)

I = Beam Current, milliamperes (mA)

beam rastering. A method of high speed beam deflection (kilohertz range or higher) used for simulated multi-beam processing (joint detection, pattern generation, multi-welds, and in situ postweld heat treatment).

beam spot. Apparent size of the beam impingement area on the surface of the workpiece (working spot size as opposed to focal spot size). See also **focal spot**.

beam voltage. Magnitude of electrical potential employed to accelerate and increase the energy of the electrons in an electron beam gun (usually expressed in units of kilovolts).

bias cup. Component of a triode gun, more electrically negative than the cathode, used as a grid to control the beam current and shape the beam. Also referred to as grid cup. See also **triode gun**.

cathode. The source of electrons, commonly a segment of tungsten or tantalum, heated to a temperature where thermionic emission occurs. Other forms and materials used as thermionic emitters include buttons or rods of tungsten, tantalum, lanthanum hexaboride, and rare earth oxides. See also **filament**.

CNC. An acronym for *Computerized Numerical Control*.

cold shut. A form of weld discontinuity caused by material solidifying at an interface before the liquid metal on either side of the interface flows together to form a continuous structure.

column valve. A vacuum valve between the electron gun and the work chamber, used to preserve vacuum and prevent contamination of the gun when the chamber is vented. Also referred to as gun valve.

conduction mode. Welding at a power density below that required to form a keyhole, where the primary method of obtaining joint penetration is heat conduction in the material being welded. See also **keyhole mode**.

convergence angle. The angle formed between the axis of the beam and the outermost electron trajectories as they approach sharp focus.

corona clear. A technique for removing contamination from the electron beam gun by using a higher than normal beam voltage. Sometimes referred to as glow discharge cleaning or gun clearing.

cosmetic pass. A partial penetration weld pass made primarily to enhance surface quality and appearance.

defocus. To locate the focal spot above or below the workpiece level when welding. See also **focus**.

degauss. To demagnetize a part or fixture in order to reduce unwanted magnetic fields.

diode gun. An electron beam gun where the cathode and grid cup operate at the same electrical potential.

downslope time. Period at end of weld during which the level of weld input power or other parameter is continuously decreased in a controlled manner.

electron beam. Electrons accelerated and shaped into a directed stream by an applied electrical potential.

Electron Beam Additive Manufacturing (EBAM). This process, also known as Electron Beam Free Form Fabrication (EBFFF) or Electron Beam Direct Manufacturing (EBDM), makes use of commercially available wire or powder as feedstock material that is melted by the electron beam. Parts are built layer by layer on a substrate until a targeted near net shape part is achieved.

Electron Beam Braze Welding (EBBW). A hybrid process that employs an electron beam to simultaneously accomplish welding and brazing, and which is sometimes used in performing T-joint welds in order to enhance the structural integrity of the joint being produced.

Electron Beam Direct Manufacturing (EBDM). See **Electron Beam Additive Manufacturing (EBAM)**.

Electron Beam Free Form Fabrication (EBFFF). See **Electron Beam Additive Manufacturing (EBAM)**.

electron beam gun. A device for producing, accelerating, and forming a directed stream of electrons. See also **diode gun** and **triode gun**.

electron beam gun column. The electron beam gun plus auxiliary mechanical, optical, and electrical components such as optics, beam alignment, focus, and deflection coils.

Electron Beam Welding (EBW). A welding process that produces coalescence of materials with the heat obtained from the kinetic energy of a concentrated beam composed of high-velocity electrons impinging on the joint. See also **electron beam welding, high vacuum**; **electron beam welding, medium vacuum**; and **electron beam welding, non-vacuum**.

Electron Beam Welding, High Vacuum (EBW-HV). An electron beam welding process mode in which welding is accomplished at a pressure of 10^{-4} to 10^{-1} Pascal [approximately 10^{-6} to 10^{-3} torr].

Electron Beam Welding, Medium Vacuum (EBW-MV). An electron beam welding process mode in which welding is accomplished at a pressure of 10^{-1} to 10^{+3} Pascal [approximately 10^{-3} to 7.5 torr].

Electron Beam Welding, Non-Vacuum (EBW-NV). An electron beam welding process mode in which welding is accomplished at atmospheric pressure.

emitter. See **cathode**.

external gun. An electron beam gun mounted outside the welding chamber. This beam is passed through the chamber wall and the workpiece is moved to accomplish welding.

filament. The term often used to describe the electron emitting component of an **electron beam gun**. See also **cathode**.

filament current. Direct or alternating current used to heat the cathode to produce electron emission.

filament kneeing. A technique used to establish space charge limited emission of the cathode and to prevent cathode overheating. Also referred to as filament peaking. See also **space charge limited emission**.

fluence. The number of electrons, or other charged particles, deposited on a surface area. It is proportional to current density x time, therefore proportional to the deposited electric charge and measured in Coulombs. It is not proportional to energy. It is not used in connection with beam power tools.

focal spot. Location where the electron beam has the smallest cross-sectional area. Also referred to as sharp focus or focal point. See also **beam spot**.

focus. Converging an electron beam to form a focal spot using electromagnetic or electrostatic forces. See also **focus coil**.

focus block. See **target**.

focusing coil. Electromagnetic coil, coaxial to the electron beam, acting as a lens to converge the beam's electrons radially to form a focal spot. Sometimes referred to as focusing lens.

gun cartridge. An interchangeable gun component allowing for filament insertion and alignment away from the welding machine.

gun-to-work distance. A linear measurement made between a reference surface, related to the electron beam gun, and the workpiece.

High-Energy-Density Welding (HEDW). Any fusion welding process utilizing a heat source capable of providing extremely high-power-density weld input levels. Welding processes that produce power densities in excess of 100 kW per square centimeter [approximately 10^6 W/in²]. See also **electron beam welding** and **specific power**.

High-Energy Electron Beam (HEEB). Term used to describe electron beams having energies in the 1 MeV to 10 MeV range. See also **fluence**.

high-voltage electron beam. A relative term normally used to identify electron beam equipment employing a beam voltage in excess of 60 kV, but under 1 MeV. See also **beam voltage** and **low-voltage electron beam**.

high-voltage tank. A container, usually filled with insulating oil, which encloses and isolates the high-voltage generating components of an electron beam system.

joint scanning. Preweld joint sensing using a low-power electron beam employed for alignment purposes.

keyhole mode. A technique that employs a concentrated heat source with sufficient intensity to vaporize some workpiece material. This results in the formation of a vapor hole (“keyhole”), surrounded by molten material that penetrates deeply into or through the workpiece. As the concentrated heat source is advanced, molten material flows around the walls of this vapor hole, fills in the trailing edge, and solidifies to produce a continuous weld.

kneeing. See **filament kneeing**.

lens. See **focus coil**.

low-voltage electron beam. A relative term normally used to identify electron beam equipment employing a beam voltage of 60 kV or less. See also **beam voltage** and **high-voltage electron beam**.

multi-beam. Employing high speed deflection as a means for utilizing a single beam to perform multiple tasks in a seemingly simultaneous manner.

mobile gun. Electron beam gun that may be moved about within the welding chamber and typically operates at 60 kV or less. Higher voltages are possible and are being explored.

oscillation frequency. The frequency at which the electron beam is deflected.

outgassing. A condition where a material, object, or one or more of their constituents has a vapor pressure greater than the surrounding environment and evaporates. See also **virtual leak**.

overpowering. Using more beam power than is required for full penetration in order to avoid sensitivity to material and equipment variations.

pulse. A brief, controlled excursion of beam-input energy generally performed in a repetitious fashion.

pump-down time. The time required to evacuate the weld chamber down to the desired welding vacuum level in high or medium vacuum variations.

pumped gun. An electron beam gun with its own directly connected evacuation system.

radiation shielding. Material to protect personnel from exposure to harmful radiation. Lead shielding or heavy-section steel is used.

radiographic window. A groove cut into a weld joint used to help verify partial penetration welds tested by radiographic methods. The groove is typically consumed and filled by the weld. When the groove is not consumed, an incomplete joint penetration or a missed joint condition is indicated.

seal weld. Any weld designed primarily to provide a specific degree of tightness against leakage.

space charge limited emission. Equilibrium condition in which any additional electron emission from additional cathode heating is prevented by electrons accumulating in front of the cathode. The cathode temperature at which emission becomes space-charge limited increases with increasing accelerating voltage. See also **filament kneeing**.

specific power. Power density in the electron beam, usually expressed in units of watts per square centimeter.

spiking. A condition in partial penetration welding where the depth of fusion is nonuniform and changes abruptly.

spot size. See **focal spot**.

target. A piece of material, usually copper or tungsten, used for electron beam impingement while setting welding parameters and during radiation leakage checks

temperature-limited emission. Condition in which beam current increases with cathode temperature and is not considered a stable emission condition for welding applications.

thermionic emission. Emission of electrons or ions by substances that are highly heated, the charged particles being called thermions. The number of thermions emitted increases rapidly as the temperature of the substance rises.

triode gun. An electron gun configuration utilizing a bias electrode, commonly called a bias or grid cup, to regulate beam current independently of beam voltage. See also **bias cup**.

upslope time. Period at start of weld during which the level of weld input power or other parameter is continuously increased in a controlled manner.

vapor plating. Condensation of metal vapors evolved during welding.

vapor shields. Optically transparent elements used to protect the optical surfaces of viewing systems or windows from the metal vapors produced during welding.

virtual leak. An apparent vacuum leak that has no communication with atmosphere.

witness lines. Scribed lines on either side of a joint used to verify weld centering on the joint. These lines may or may not be consumed during welding, allowing for postweld inspection.

Supplemental terms and definitions are included in Annex C, Extended Glossary for Electron Beam Processing.

4. Safety Considerations

4.1 Scope. These safe practice recommendations are intended to provide a baseline for owners and users of electron beam welding equipment to enhance operator safety. This clause gives a set of minimum standards to observe in order to protect personnel and property from the potential hazards specifically associated with EBW. No attempt is made to include all the potential hazards associated with welding processes in general, which are covered by ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, nor all the OSHA regulations established to protect personnel working on (or around) various forms of industrial machinery and vacuum equipment. Additional safety information may be provided by the equipment manufacturer or integrator.

4.2 Potential Hazards. The following potential hazards specifically related to EBW are included within the scope of these recommendations:

- (1) Electric shock
- (2) X-radiation
- (3) Fumes and gases
- (4) Visible radiation
- (5) Vacuum
- (6) Thermal hazard
- (7) Mechanical hazards
- (8) Confined space

4.2.1 Electric Shock. The voltages employed in EBW machines are sufficient to cause fatal injury to personnel. All electrical equipment associated with EBW machines should be installed in accordance with the American National Standards Institute (ANSI) specification NFPA 70, *National Electrical Code*, with primary reference to Article 660; and in accordance with the National Fire Protection Association specification NFPA 79, *Electrical Standard for Industrial Machinery*.

All doors and access panels on EBW equipment should be properly secured (electrically or mechanically) to prevent access by unauthorized persons to electrical components. All conductors operating at the accelerating potential shall be fully enclosed by grounded, conductive barriers that are interlocked to prevent access during operation. Before servicing the electron gun and high-voltage power supply components is permitted, a grounding probe shall be used to ensure complete discharge of all components. This grounding probe shall be left connected to the high-voltage terminal at all times when servicing the high-voltage power supply. Wherever access to high voltage is possible, the area should be properly posted in accordance with ANSI Z535.1, *Safety Color Code*, ANSI Z535.2, *Environmental and Facility Safety Signs*, and ANSI Z535.5, *Accident Prevention Tags*.

4.2.2 X-Radiation. X-radiation is produced when electrons collide with a substance such as a gas or a metal. In the case of electron beam equipment, the majority of X-rays are produced when the beam impinges upon the workpiece, back-up bars, tooling, or fixturing. Lower levels are produced when the beam strikes gas molecules or other substances

along the beam path to the workpiece, back-up bars, tooling, or fixturing. The intensity of the X-rays produced increases with increasing beam voltage, beam current, and the atomic number of the material struck by the beam.

Whenever the electron beam is on, the system is capable of generating X-rays. These X-rays are produced mainly in the workpiece, back-up bars, tooling or fixturing, the electron beam gun column, and the work chamber. X-rays are produced by older high-voltage power supplies that employ high-voltage electron tubes. If electron beam equipment is improperly shielded or improperly used, X-ray leakage can result in personnel being exposed to a radiation dose sufficient to cause injury. Wherever lead is employed as a radiation barrier, it should be mechanically supported and properly protected from the possibility of accidental damage. Lead glass viewing ports should be protected from pitting and buildup or cracking due to hot spatter impinging on them.

Publications governing safe operation of X-ray-producing equipment (for example, ANSI/HPS N43.3-2008, *For General Radiation Safety—Installations Using Nonmedical X-ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV*) list the typical precautions and procedures that should be followed in order to provide adequate personnel protection.

Before shipping, the manufacturer should make a complete X-radiation survey of the electron beam equipment to assure compliance of the equipment with all radiation regulations and standards applicable to the site where the machine will be installed.

This survey should be made while the machine is operating at full-power conditions:

(1) With the beam current and beam voltage of the electron gun adjusted to the normal maximum capability of the equipment.

(2) With the electron beam impinging upon a tungsten target and with the beam spot grossly defocused to minimize penetration into the target. The equipment shall not be used to weld materials of higher atomic number than that of the survey target.

(3) With the electron gun and the target positioned within the normal travel capabilities of the gun and work carriages, so that the beam spot on the target is located as close as possible to the area of the machine being surveyed for its radiation leakage level.

Review the Radiation Survey for the machine you are using, or request one from the manufacturer if you don't have one, to ensure that the equipment can be operated in the intended location and manner.

The test conditions and results of the machine manufacturer's radiation survey should be documented and supplied to the machine user. An example of a form for such a survey is given in Figure 1.

Date Survey Performed: _____

Survey Performed By (Name): _____

(Title): _____

Survey Meter Used (Mfg./Model): _____

(Serial No.): _____

Calibration of Meter (last calibration): _____

(recalibration due): _____

The radiation level in the area around electron beam unit Manufacturer's Serial #: _____

being produced by its beam working at its maximum rated voltage _____ (kV) and maximum rated current _____ (mA),

upon a _____ (material) target, is certified to have been measured to be no greater than _____ (mR/h) at any point

around the machine, when surveyed at a distance of no farther than _____ (mm [in]) from the machine's exterior surfaces.

Additional Comments (if required): _____

Figure 1—Sample Form for Radiation Survey

Following the installation of an EBW machine at a user's facility, and prior to its certification as a fully operational piece of equipment, a complete radiation survey of the installation should be made jointly by supplier and user, under full power conditions, to assure that the maximum radiation leakage of the final installation meets all applicable regulations and standards. Also, a resurvey and recertification should be made after any modifications to the chamber, the electron beam gun column, or to the radiation shielding.

Electron beam equipment should be inspected periodically to verify that all radiation barriers (such as shielding, safety interlocks, and warning devices) are intact and functioning properly. These precautionary periodic radiation surveys can be made while the machine is performing its normal welding or cutting operations and do not necessitate recertifying the machine to full power conditions. During such periodic surveys, particular attention should be focused on critical places such as access ports, viewing windows, vacuum ducting connections, service feed through ports, and shielding joints, where radiation leaks might possibly occur.

Continuously operating equipment employing moving radiation shielding to enhance product throughput should be checked regularly to ensure that the shielding is not deteriorating due to cyclic motion, and to verify that radiation levels around the equipment do not exceed permissible values. The results of all of these inspections and checks should be recorded and maintained on file.

Special precautions are required in conducting a radiation survey. Not only is the accuracy of radiation survey instruments affected by electric and magnetic fields, but the validity of the measurements is also strongly dependent on the type of instrument (energy range capability) and sweep rate (meter response time) employed. Personnel properly trained to do these surveys using calibrated test equipment should carry out radiation surveys.

Several standards exist for classification of radiation installations. Table 1 gives an example of the interpretation of one such standard. However, each user should determine what regulations and standards apply directly to his or her specific installation and should abide strictly by those regulations and standards.

4.2.3 Fumes and Gases. Toxic fumes and gases may be generated by electron beam equipment. Specifically, ozone (O_3), various oxides of nitrogen (in particular, NO and NO_2), and workpiece material fumes are generated. All necessary environmental engineering measures necessary for fume and gas control (external venting, filtering, etc.) should be taken to prevent the accidental inhalation of harmful concentrations of fumes and gases by personnel working on, in, or around this type of electron beam equipment. Exhaust of these fumes may violate local or federal standards, and implications should be considered before using equipment.

Particulate material deposited on fixtures in (and walls of) the workpiece enclosure during equipment operation can become airborne when disturbed. Depending on the nature and concentration of these particles, a possible health hazard to personnel entering the enclosure may be created. In the case of non vacuum and medium vacuum welding, personnel

Table 1
Radiation Exposure Standards

The following provides a guide to the maximum permissible survey instrument safe reading allowable # as interpreted from ANSI/HPS N43.3, *For General Radiation Safety—Installations Using Nonmedical X Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV*, expressed in microsievert per hour ($\mu Sv/hr$). The $\mu Sv/hr$ is the metric unit of measurement registered by the readout scale on most radiation survey instruments. The values in the table are cited as examples from N43.3-2008, but refer to the latest edition of N43.3 for the current requirements.

Controlled Area—limited occupancy (area under supervision, length and frequency of exposure are controlled)	20 $\mu Sv/hr$ [2 mR/hr]: Max. at 5 cm [2 in] from outside surface of shielding
Controlled Area—continuous occupancy (area under supervision, length, and frequency of exposure not controlled)	5 $\mu Sv/hr$ [0.5 mR/hr]: Max. at 5 cm [2 in] from outside surface of shielding
Uncontrolled Area—continuous occupancy (area not supervised, and no control over length or frequency of exposure)	2 $\mu Sv/hr$ [0.2 mR/hr]: Max. at 5 cm [2 in] from outside surface of shielding

should not be allowed to enter the chamber enclosure after welding until concentrations of airborne contaminants (particularly, ozone, oxides of nitrogen, and other toxic gases) that may be present have been reduced to safe levels.

Materials that can be welded by the electron beam process include some with well known toxic properties (beryllium, for example). The possible toxic properties of a workpiece should be determined prior to processing with an electron beam, and adequate protection should be provided to personnel in accordance with ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes* and any other local regulations. Before welding any unfamiliar material, the Material Safety Data Sheet (MSDS) should be read to determine whether any hazards exist.

It is very unlikely that the air left in a high vacuum electron beam chamber would be sufficient to give rise to ozone and oxides of nitrogen in concentrations above the permissible exposure level as given in the *Code of Federal Regulations*. However, adequate area ventilation should be employed to maintain concentrations of airborne contaminants around the equipment below permissible exposure levels, and proper exhausting techniques should be employed to maintain residual concentrations in the chamber (or enclosure) below these same limits. Likewise, care should be taken while cleaning the interior of the vacuum chamber to ensure that fumes from the solvents and cleaning solutions do not reach hazardous levels.

When employing EBW-NV mode, where welding is done in atmosphere (and thus where concentrations of ozone and oxides of nitrogen could easily exceed permissible limits), an externally vented weld area exhaust system should be employed.

4.2.4 Visible Radiation. Direct viewing of visible radiation emitted during operation of electron beam equipment can be harmful to eyesight. Since the intensity of the emitted light varies with the electron beam power and the composition of the workpiece, no precise guidelines can be stated. Infrared and ultraviolet radiation is normally a viewing hazard, but the leaded glass used in electron beam equipment viewing ports and optical systems provides sufficient protection.

Light emitted during EBW is produced by radiation from the molten metal in the weld pool. The intensity of radiated light increases with the temperature of the metal. Since the visible light emitted during welding on high-melting point materials is too bright for direct viewing, special care shall be taken to ensure that an adequate eye protection filter is employed. Guidelines for selecting a suitable filter are difficult to establish, due to many factors that affect the choice. These factors include the distance and angle of viewing, optics employed (magnification, aperture, etc.), workpiece material, and beam power. However, as a general guideline, the filter used should be of sufficient density so that the viewer's eyes are comfortable during the highest level of light intensity encountered and so that there is no evidence of eye irritation after exposure.

In the presence of intense light, proper eye protection is necessary, and optical viewing systems should be provided with filtering in accordance with ANSI/ASSE Z87.1, *Occupational and Educational Personal Eye and Face Protection Devices*. All persons involved with EBW equipment should be instructed in the use of proper optical filtering and should be required to use such protection.

4.2.5 Vacuum Safety Precautions. All EBW machines require a high vacuum for beam generation. Most machines require some level (i.e., either a high or medium type) of vacuum environment for the workpiece. Consequently, users of the EBW process should take care to observe the same safety precautions as users of conventional vacuum systems and vacuum-associated equipment. A detailed description of these precautions is provided by AVS (formerly American Vacuum Society) in its *Vacuum Hazards Manual*.

4.2.6 Thermal Hazards. Metal fusing processes such as EB welding can produce significant heating of the weldment, fixtures, or ancillary devices such as the tungsten focus target. The handling of these components may require the use of personnel protective equipment such as gloves. Other considerations should be taken when removing hot components from the welder and the location or storage of combustible materials within the EB welder working space. Oil diffusion pumps and other devices such as vacuum gauges can produce significant heating that should be considered during maintenance, troubleshooting, or repair.

4.2.7 Mechanical Hazards. Various mechanical hazards are present within these systems. The translation of the part with respect to the beam can produce high speed or high inertial forces which can endanger personnel or damage equipment, particularly during setup or testing outside the EB chamber. Proper engineering controls and administrative procedures should be employed to reduce these hazards to acceptable levels. Guards, barriers, and markings may be used to control or prevent access to external hazards. Those controls provided by the manufacturer should not be removed or altered without the proper reassessment of the hazards.

4.2.8 Confined Space Hazards. Large chamber machines may present confined space hazards. Confined spaces can alter the effect of otherwise controlled hazards such as fumes, or entrapment and therefore require special consideration. These hazards are often mitigated with administrative and engineering controls such as special work permits and two man operations. Consult local regulations regarding definitions and regulations of this type of hazard.

5. Process Fundamentals

5.1 Description of Process⁴

5.1.1 Formation of an Electron Beam. This section briefly describes the “electron source” of the electron beam welding process, e.g., the electron beam gun. Electrons are generated in a vacuum enclosure by heating the cathode, a negatively charged emitter, to its thermionic emission temperature causing electrons to “boil off” the filament. As the temperature is increased, more electrons are emitted from the cathode until a maximum emission level is reached. 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 as shown (see Figure 2). The combination of all three of these components constitutes an electron beam gun.

⁴For a more detailed discussion, see O’Brien, A., ed., 2007, *Welding Processes—Part 2, Chapter 13*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

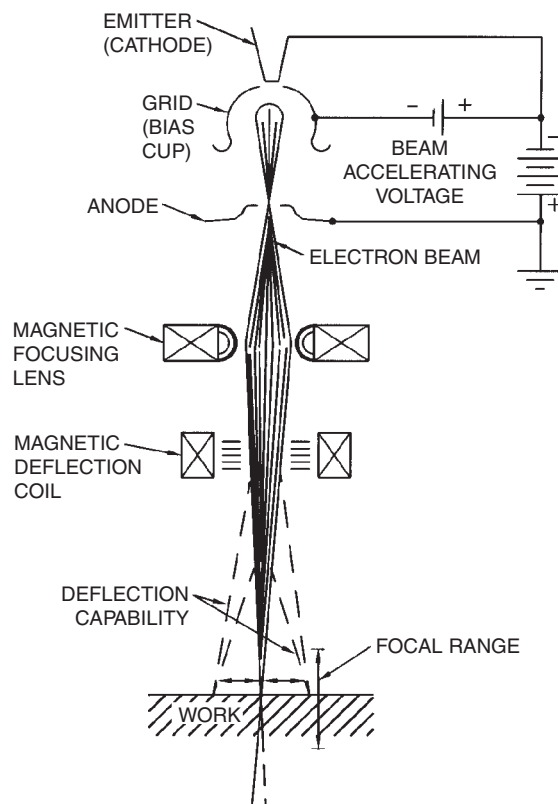


Figure 2—Simplified Representation of an Electron Beam Gun Column

In a diode gun, the bias (or grid) 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 grid cup is at another, and this potential difference (bias voltage) between the two is used to control the beam current. When the grid cup is biased more negatively than the cathode, electron flow is inhibited and beam current reduced. Conversely, as the difference in negative biasing voltage is reduced, beam current output will be increased. In both gun designs, electrons are accelerated towards an anode (which is at ground potential) and pass through it to exit the gun. 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.

5.1.2 Control of the Electron Beam. Since electrons are charged particles, their direction of travel can be controlled by the use of electromagnetic fields. When the accelerated beam of electrons emerges from the aperture in the anode, it begins to diverge because of mutual repulsion and other causes. An electromagnetic coil (located below the anode) is used to focus the beam of electrons. Thus, by simply varying the current applied through this focusing coil, the electron beam can be focused at any desired location beyond the plane of the focus 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 other means to control the deflection coils, thus providing a versatile method for controlling beam movement. Recent advances in high speed beam deflection have facilitated the use of dynamic pre- and post-heating, thereby providing the capacity to alter the temperature/stress distribution adjacent to the weld and thus minimize cracking in some alloys.

Beam focus condition and deflection can be varied by both manual and automatic input control means. This variable control combined with an optical or video view of the weld region is a particularly powerful feature of the EBW process for the development and selection of weld parameters. Process stability can be greatly enhanced by the real time adjustment of these parameters to stabilize and “fine tune” the process conditions. Other benefits include reduction of spatter, undercutting, voids and cold shuts at the weld root. The weld profile can be altered to produce a wide range of weld shapes to accommodate joint fit-up, shrinkage, or cosmetic appearance.

5.1.3 Weld Formation. Numerous studies have been conducted to determine exactly how the weld is formed by the electron beam striking the workpiece. The high energy density of the focused beam vaporizes some of the material on which it impinges. A keyhole forms (see Figure 3) in a steady state condition between the pressure of this expanding vapor and the surface tension of the molten material surrounding the keyhole. 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 provides high power density EBW with the unique capability to produce deep, narrow welds and narrow heat-affected zones resulting in minimized distortion of weldments. This type of energy transfer is referred to as keyhole mode welding. These same penetration characteristics can cause defects in electron beam welds; for example, instability of metal flow or trapped gas in the keyhole can result in cold shuts, porosity, or irregular penetration. However, employment of today’s modern beam power input control techniques tends to appreciably reduce the occurrence of such defects by allowing a wide selection of process variable combinations to stabilize the keyhole and produce sound, defect free welds.

In contrast, lower energy density beam spots result in wider, shallower welds with aspect ratios typical of arc welds. This latter mode of energy transfer is called the conduction mode; this mode of welding has been utilized to provide very smooth bottom bead weld characteristics in complex assemblies (such as Niobium accelerator components) where bottom bead machining access is limited—and where the material is typically no more than 6 mm [0.24 in] thick.

5.1.4 Welding Variables. In EBW, the primary welding parameters are beam voltage, beam current, travel speed, and focus coil current. Secondary variables are vacuum level, gun-to-work distance, and oscillation of the beam spot. The energy conversion efficiency of electron beam welding is higher than that for arc and laser beam welding processes. A lower energy input can be used to give equivalent penetration with EBW as that achieved with conventional arc and laser beam welding processes at higher energy inputs. Variables typically held as constant include material chemical composition, cleaning method, surface conditions, joint fit-up, beam to joint alignment, fixturing, and heat sinking. As with all welding processes, small changes in any of these process parameters may produce large variations in the weld. Therefore, strict control is required to assure consistent process performance.

Although high power densities can be a powerful tool for EBW, precise control is required because of the strong influence they can have on the weld geometry. Thus, variations in weld penetration, from machine to machine or in the same welding machine over time, can often be traced to small differences in power density that occur even when all measured

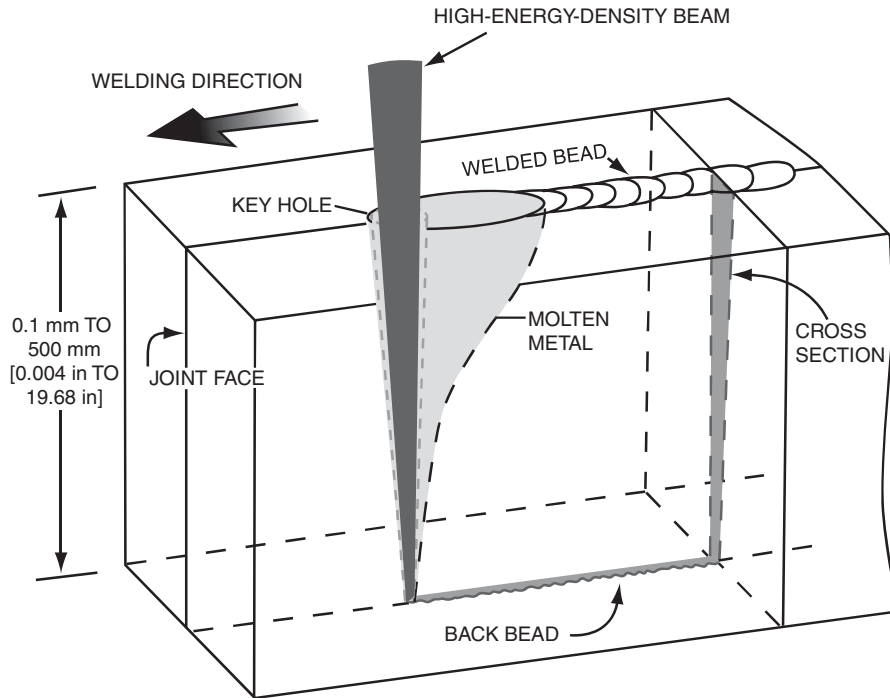


Figure 3—Schematic Representation of a Keyhole Weld

welding parameters (accelerating voltage, beam current, focus coil current, and travel speed) appear to remain constant. Consequently, in critical applications, care should be taken to ensure that the filament installation, chamber pressure, beam deflection, and gun-to-work distance are well controlled and repeated.⁵ Electron beam diagnostic tools, designed to measure the power density distribution, are also available and have been used in selected critical applications.

5.2 Areas of Application. When EBW was initially introduced to industry in the 1950s, the nuclear and aerospace industries were the primary users. These industries had an urgent need to significantly improve the quality and reliability of the parts they produced. Consequently, these two industries were quick to recognize the ability of EBW to minimize thermal distortion, weld zone shrinkage and heat-affected zone width during welding. A decade later, the automotive and consumer products industries also began using the EBW process as it had the proven ability to weld at much higher speeds than most any other welding process and could significantly increase productivity in mass production.

At the time of publication of this document, the EBW process is regularly employed both inside and outside a vacuum by a broad variety of industries worldwide for a wide range of joining tasks. It is universally recognized to be a fast, accurate, and highly reliable fusion welding process. Numerous examples of current industrial applications of the EBW process are found in Clause 13, Practical Examples.

5.3 Advantages and Limitations. Like other welding processes, EBW has both advantages and limitations that the user should bear in mind when considering the process for any application.

⁵ For a definitive explanation of how variations in these operational parameters can affect performance, see LaFlamme, G. R. and D. E. Powers, 1991, Diagnostic Device Quantifies, Defines Geometric Characteristics of Electron Beams, *Welding Journal* 70(10): 33–40.

5.3.1 Advantages of Electron Beam Welding.

(1) The focused electron beam results in a very high energy density at the spot where the beam strikes the workpiece. It is possible to concentrate the incident beam into a very small area, thereby producing maximum energy densities of about 100 to 1000 times higher than arc welding heat sources. High power beams in excess of 30 kW have been produced and can be used to weld very thick sections with a single pass.

(2) Because of the high energy density, the total energy input is relatively low. This characteristic allows welds to be made that have less shrinkage and distortion, narrower heat-affected zones, and less thermal effects on adjacent material compared to arc welding. High welding speeds are made possible.

(3) High aspect-ratio (ratio of depth to width) welds may allow single-pass welding where arc welding would require multi-pass welding with consumables.

(4) Welding in a high-vacuum environment minimizes atmospheric contamination of material where this is particularly undesirable.

(5) The high power densities available allow the welding of high thermal conductivity materials, refractory metals, and many dissimilar metal combinations that are extremely difficult or impossible to weld with conventional fusion welding processes.

(6) High-vacuum welding allows items to be sealed with a vacuum inside.

(7) The control and versatility of the process provide the capability for performing a wide range of applications with a single welding machine. The versatility of the beam control allows a tuning of the heat source to optimize weld characteristics and minimize weld defects.

(8) In comparison with laser beam welding, the process is much more efficient in material melting per kilowatt and does not suffer from the beam energy reflection problems of LBW in materials such as copper and aluminum alloys.

(9) It further reduces or eliminates oxygen or hydrogen pickup by the weld metal.

5.3.2 Limitations of Electron Beam Welding.

(1) An electron beam welding system costs much more than a conventional arc welding system.

(2) With its narrow weld zone, parts and fixturing usually require higher precision in machining and setup than for conventional welding.

(3) When welding inside a chamber with high vacuum, the evacuation time can be a significant factor in production costs.

(4) Equipment shall incorporate appropriate shielding to protect personnel from X-rays generated by the electron beam. To ensure the integrity of this shielding remains intact, EBW equipment shall be monitored periodically.

(5) Because the electron beam is deflected by magnetic fields, some dissimilar material combinations that impose a thermo-electromotive force at the weld joint may be difficult to weld. Furthermore, ferromagnetic materials cannot be welded without careful degaussing. Fixturing should also be made from nonmagnetic materials.

(6) In high power density welding, weld discontinuities (such as spiking) associated with root porosity may occur. These discontinuities are particularly prevalent in partial penetration welds.

5.4 Allied Processes.⁶ Other adaptations of the electron beam process include electron beam braze welding (EBBW) and electron beam machining. Machining encompasses electron beam cutting (EBC) and drilling, the deposition of supplementary weld metal (surfacing, cladding, and hard-facing), electron beam additive manufacturing (EBAM), surface texturing, and heat treating of components.

5.4.1 Electron Beam Braze Welding. Electron beam braze welding (EBBW) is a variation of braze welding (BW), a joining process that uses a filler metal with a liquidus above 450°C [840°F] and below the solidus of the base metal. The

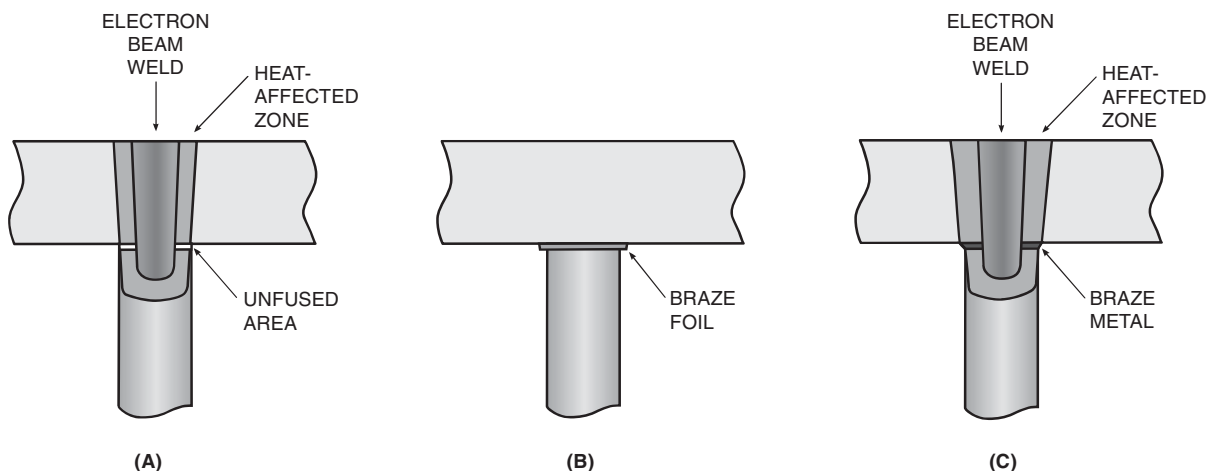
⁶ Adapted from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

base metal is not melted. Unlike conventional braze welding, where the filler metal is distributed in the joint by capillary action, electron beam braze welding uses an electron beam as a heat source for simultaneously producing a brazing action and a welding action. A specific application of this hybrid technique uses an electron beam welding machine with computer numerical control capability to make it possible to produce high-quality welds in assemblies with complex designs. It can be used to eliminate the notch effect caused by incomplete fusion in some areas of T-joints where EBW alone is used. The stress riser normally resulting from the notch effect is appreciably reduced, and additional joint strength is achieved because of the bonding of the brazing alloy with the two workpieces. Electron beam braze welding was initially developed to make T-joints in components of centrifugal compressor impellers for the oil, gas, and petrochemical industry.⁷ An example is shown in Figure 4. To join the impeller covers to the blades, a piece of brazing foil was inserted between the faying surfaces of the cover and the blade; then the assembly was welded with EBW. Figure 4(A) shows the assembly of the joint between the impeller blade and the cover. Figure 4(B) shows the placement of brazing foil, and (C) shows the completed joint. Complete fusion is achieved, as shown in the cross section of the joint in Figure 5.

5.4.2 Electron Beam Cutting. Electron beam cutting (EBC) is a thermal cutting process that severs metals by melting them with the heat from a concentrated beam, composed primarily of high-velocity electrons, impinging on the workpiece. Electron beam cutting is not discussed in detail here because of its limited use, but is mentioned as a variation of the electron beam process.

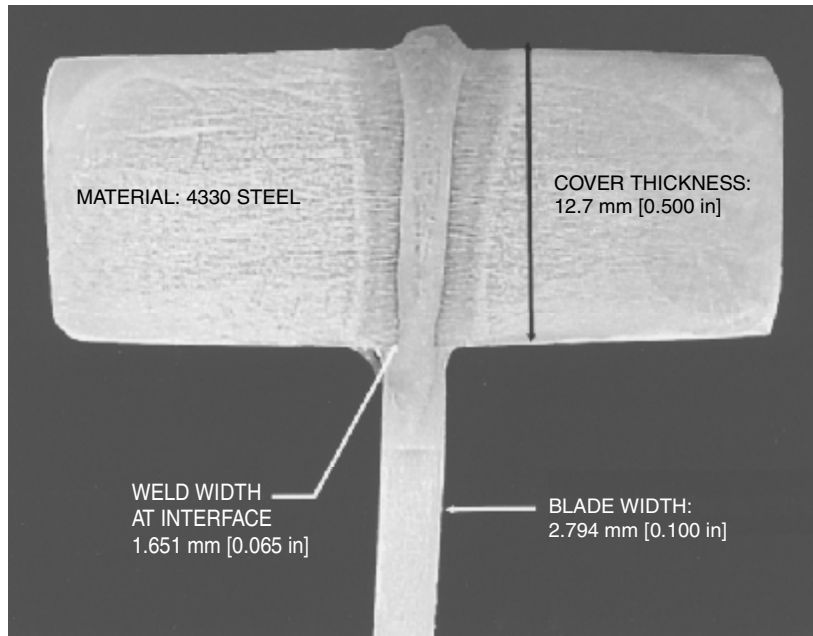
5.4.3 Electron Beam Drilling. The sequence of electron beam drilling is illustrated in Figure 6, from the impingement of the electron beam on the workpiece to the expulsion of molten material and finished hole. A highly concentrated electron beam spot on the order of 10^8 W/cm² (10^9 W/in²) or greater is pulsed in a highly reproducible fashion and is employed as means of rapidly creating a relatively parallel-sided vapor channel. Concurrently, some form of backing material is used to assist in ejecting the molten material surrounding the vapor channel. By combining high-speed beam deflection and CNC workpiece motion control, serially drilled holes can be produced at extremely high rates (approximately 3,000 holes/s). Figure 7 shows an application of electron beam drilling, a spinner used in the production of fiberglass that has over 25,000 holes, which are 0.55 mm (0.02 in) in diameter.

⁷ Myers, L. W. and G. R. LaFlamme, "Electron Beam Braze Welding of Compressor Impellers" Taiwan International Welding Conference on Technology Advancements & New Industrial Applications in Welding, Taipei, Taiwan, R.O.C., 7–9 September, 1998.



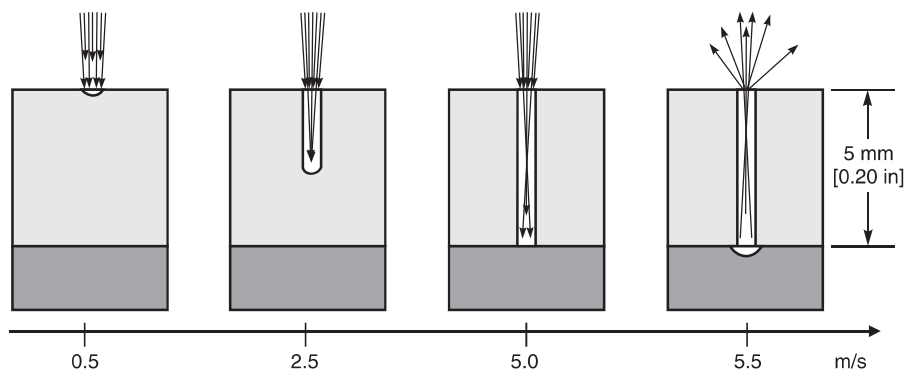
Source: Reproduced from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

Figure 4—(A) Impeller Blade and Cover Assembly, (B) Placement of Braze Foil, and (C) Cross Section of Completed Braze-Welded Joint



Source: Reproduced from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

Figure 5—Finished T-Joint of Thin Impeller Blade and Thick Cover Joined with a Combination of Electron Beam Welding and Brazing



Source: Reproduced from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

Figure 6—Sequence of Electron Beam Drilling with Speed of Beam Travel, Expulsion of Metal, and Completed Hole



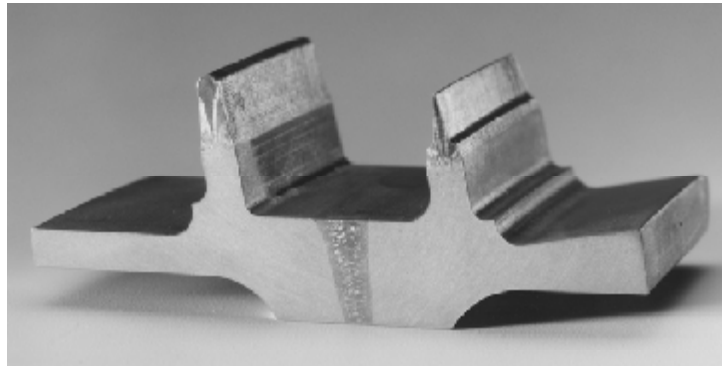
Source: Reproduced from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

Figure 7—Spinner with 25,600 Holes 0.55 mm [0.022 in] Diameter Drilled by the Electron Beam Process

5.4.4 Electron Beam Surfacing, Cladding, and Hardfacing. In electron beam weld cladding, surfacing, and hardfacing, metal (usually in wire form) is fed into the electron beam impingement spot to cause the metal to be rapidly deposited on the surface of the workpiece in a highly controlled fashion, thus quickly building up the desired quantity of metal in the precise region desired. This method traditionally has been employed to accomplish knife-edge seal repair tasks. Figure 8 shows a repair weld made with titanium wire on a titanium drum rotor section of an aircraft engine. The section on the left shows the initial metal buildup as deposited; the section on the right shows the welded product, finished by postweld machining.

5.4.5 Electron Beam Additive Manufacturing (EBAM). Figure 9 shows a cost effective process that utilizes proven Electron Beam Welding technology to create metallic parts. Using modern CAD modeling capabilities, EBAM deposits feedstock material in an additive layering process to produce near-net-shape pre-forms. The deposition path and process parameters are generated from post-processing the virtual 3D model and executed by a real-time computer control. The deposition takes place in a vacuum environment, typically in the range of 1.3×10^{-2} Pa to 1.3×10^{-3} Pa [1.0×10^{-4} to 1.0×10^{-5} Torr]. The wire is directed toward the molten pool and melted by a focused EB. Parts are built up layer by layer by moving the EB and wire source across the surface of the underlying material that is commonly referred to as the substrate, as shown in the illustration. The substrate material can become an integral part of the finished product. In this manner, free-standing shapes, or preforms, are generated without molds or dies. Conventional techniques are then used to machine the preform to the final part geometry.

The ability to rapidly procure components for the aerospace industry is severely limited by the lead-time for raw materials, tooling (casting molds and forging dies, etc.), design, and the actual manufacturing of components. EBAM has the potential to greatly reduce the manufacturing lead-time and cost for components by reducing the volume of materials required along with the resulting machining time, eliminating the need for hard tooling, and improving the flexibility of the design process. These processes are ideally suited to a wide range of aerospace materials including many reactive and refractory alloys. Refer to the practical examples in Clause 13 to note an EBAM application of a chord section of an aircraft and an EBAM of a jet engine case knife edge seal.



Source: Reproduced from O'Brien, A., ed., 2007, *Welding Processes—Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami, Florida: American Welding Society.

Figure 8—Repair Welds on Titanium Drum Rotor Part of an Aircraft Engine, As-Welded (Upper Left Section) and Finished Product After Machining (Upper Right Section)

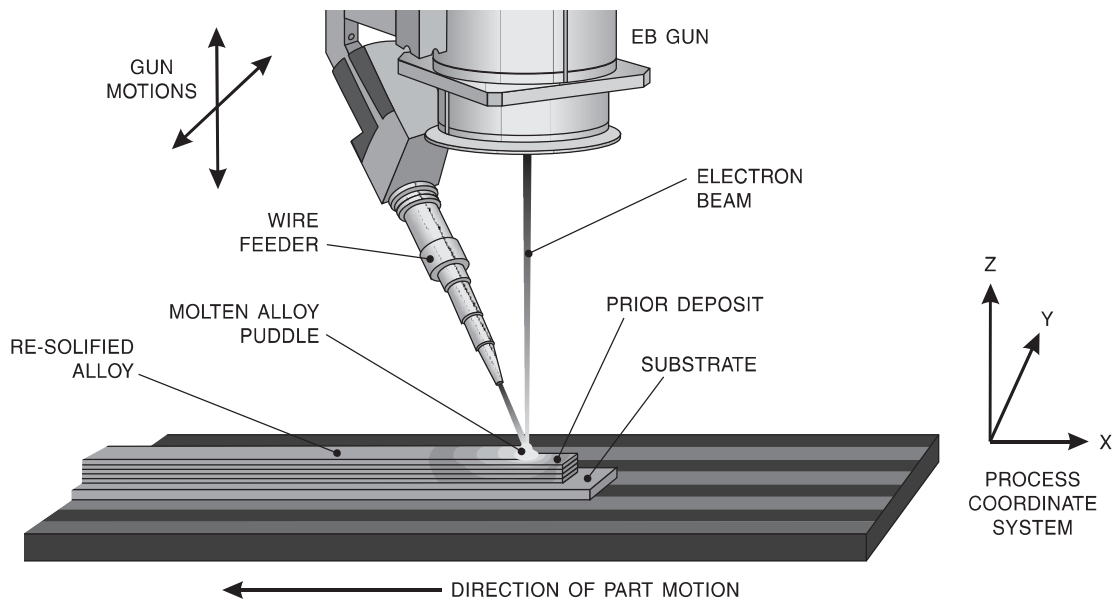


Figure 9—Schematic Representation of EBAM Process

5.4.6 Electron Beam Surface Texturing. EB surface texturing (or sculpturing) is a technique which, as with EB drilling, utilizes both rapid beam pulsing and high speed deflection to remove material, not for the purpose of producing holes, but rather to form “hills” and “valleys” on the workpieces’s surface. This process is presently used by aircraft manufacturers to provide a better bonding seal between composite materials being “glued” on to metal aircraft structures (see Figure 10).

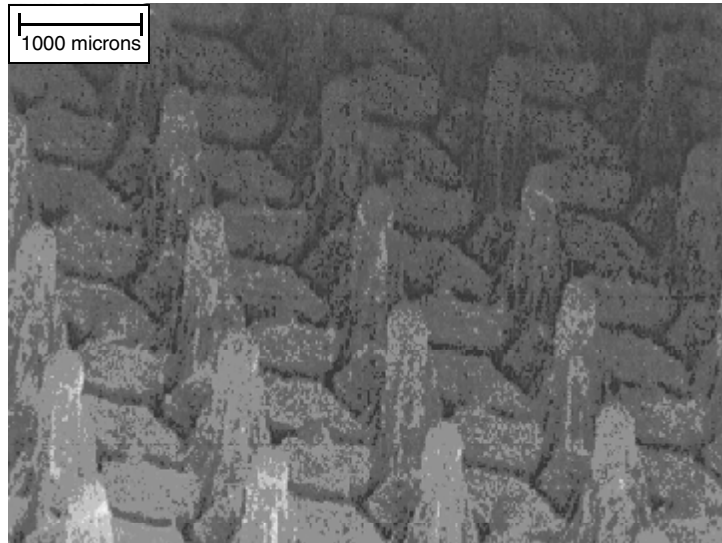


Figure 10—Example of EB Textured Surface

5.4.7 Electron Beam Heat Treating. Since an EB provides both a fast and efficient, as well as a highly versatile means for delivering energy to a workpiece it is often utilized for performing a number of thermal surface type industrial processing applications where the beam is used as the source of energy input needed to initiate a physical change to the surface the beam is being impinged upon. One such form of industrial use of this type of capability is that of utilizing the beam for performing a surface hardening task, either one of a rapidly heating and quenching phase transformation type or one of a rapidly melting and resolidifying “glazing” type (see Figure 11).

For the conventional phase transformation hardening type, a rapidly scanned (either continuous or pulsed) beam is used to rapidly heat a specific area within seconds to a temperature above the transformation (but below the melting point) temperature of the workpiece; then, when the beam is extinguished, this heated area is quickly self-quenched by the still cool bulk portion of the workpiece producing a hardened surface segment. For glazing, the beam’s heat input is used to quickly melt a specific area of the workpiece surface which then, when beam is extinguished, rapidly re-solidifies to form the hardening effect desired.

With phase transformation hardening, the level of hardness achieved depends on the percentage of carbon content in the material being treated and the depth of hardness attained by adjusting both the beam’s energy input and interaction time in a highly controllable fashion. With glazing, since the beam input energy and reaction time are carefully controlled to rapidly melt and resolidify a thin layer of the workpiece’s surface, and thereby forming a “metallic glass” like surface layer having an extremely high hardness value, it can be utilized for the purpose of surface hardening on materials of both a carbon and noncarbon content nature. In both these cases the EB is able to quickly input, in a very precisely controlled fashion, the exact amount of energy needed to heat the treated area to the exact temperature required. In general, in order to utilize the greatest degree of beam versatility, both these methods are accomplished in some sort of a vacuum environment, either one having the same order of magnitude as that required for beam generation or one that has somewhat of a lesser degree of vacuum value than that required for generating the beam.

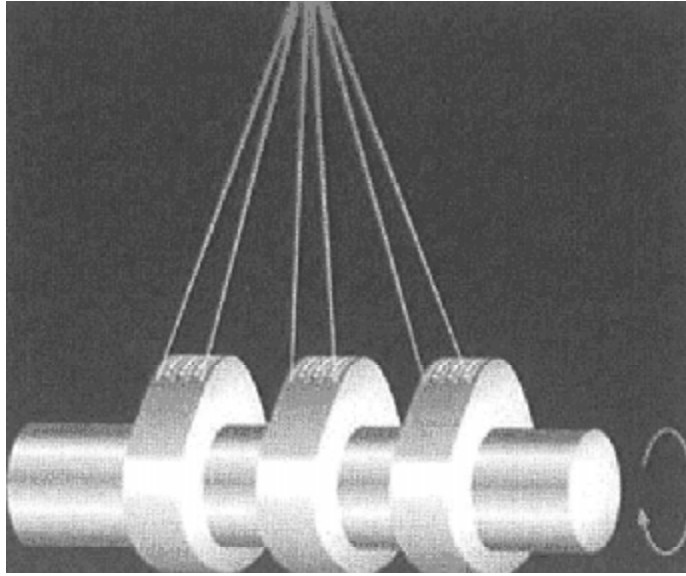


Figure 11—Example of EB Simultaneous Heat Treatment

6. Description of Equipment

6.1 Introduction. Electron beam processing can be performed both in and out of vacuum utilizing fixed or mobile guns with high or low beam voltages (see Figures 12 and 13). This section describes the three modes of EBW, differences between high- and low-voltage machines, and components making up an EBW system.

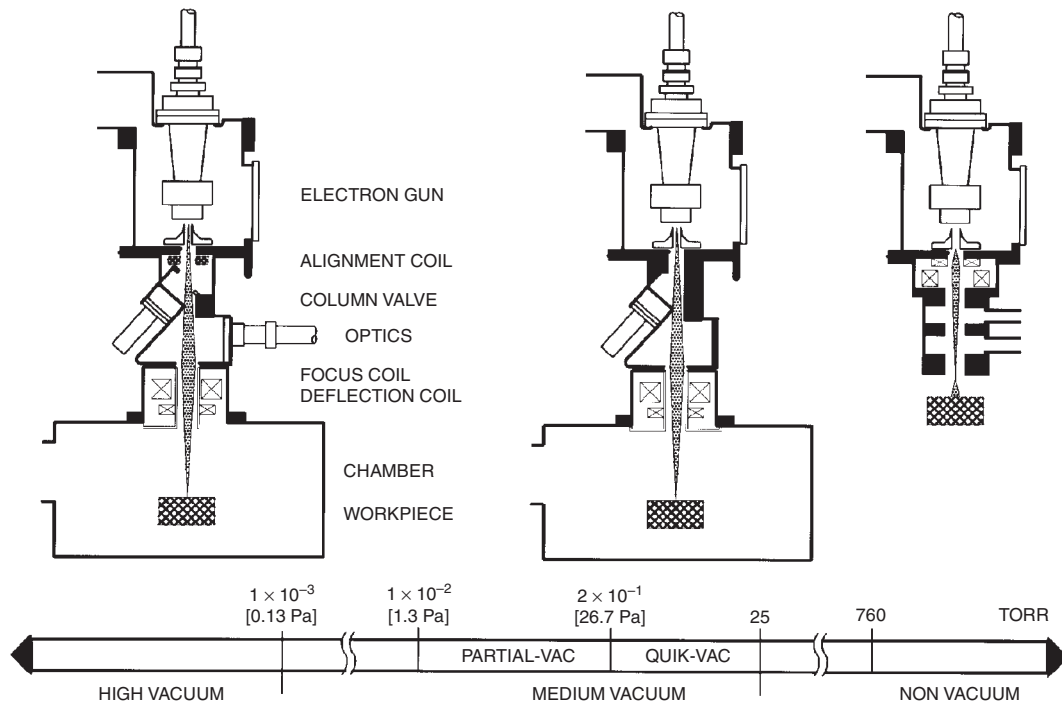
6.2 Modes of Electron Beam Welding. The vacuum level at which welding takes place determines the process mode and therefore, the type of equipment required.

6.2.1 High Vacuum Electron Beam Welding (EBW-HV) (1.3×10^{-1} Pascal [1.0×10^{-3} torr] or lower). When the electron beam was initially employed for materials joining, welding had to be performed in exactly the same environment needed for beam generation, e.g., an ambient vacuum of 1.3×10^{-1} Pascal [1.0×10^{-3} torr] or lower. This mode of electron beam joining of materials, now referred to as high-vacuum electron beam welding (EBW-HV), provides the type of high quality weldments for which EBW is usually noted.

The time required to produce a vacuum environment around the workpiece is influenced by the size of the welding enclosure (dictated by the part geometry and gun configuration) and vacuum pumping system being employed. The evacuation time required on EBW-HV machines is anywhere from a few seconds up to 30 minutes. The time required to evacuate the welding enclosure to the operating vacuum level needed is important, since it is generally viewed as unproductive. However, in large chamber EBW applications, this evacuation time can be utilized for verification of workpiece programmed moves. In addition, multiple pumping systems may be incorporated to reduce the effective pump-down duration.

6.2.2 Medium-Vacuum Electron Beam Welding (EBW-MV) (1.3×10^{-1} to 3.3×10^{-1} Pascal [1.0×10^{-3} to 2.5×10^{-3} torr]). One means devised for reducing the required evacuation time is the use of medium vacuum mode EBW (EBW-MV). In this mode of operation, welding is accomplished at a vacuum level that is at least an order of magnitude higher in pressure than that needed for beam generation, i.e., in the range of 1.3×10^{-1} to 13 Pascal [1.0×10^{-3} to 1.0×10^{-1} torr].

EBW-MV requires that the beam generation and workpiece regions be isolated from each other by use of a vacuum divider (an aperture sized to impede gas flow without restricting beam passage). The two individual vacuum zones produced by employing a vacuum divider should be evacuated by separate pumping systems. Operating in this fashion, the beam may still be generated in a high-vacuum environment while the workpiece surroundings need not be evacuated to a



*Refer to Annex A for cross reference of various pressure units.

Figure 12—Electron Beam Modes of Operation

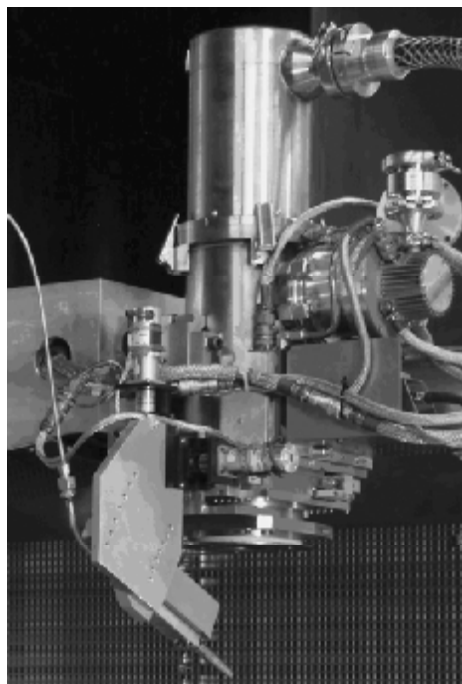


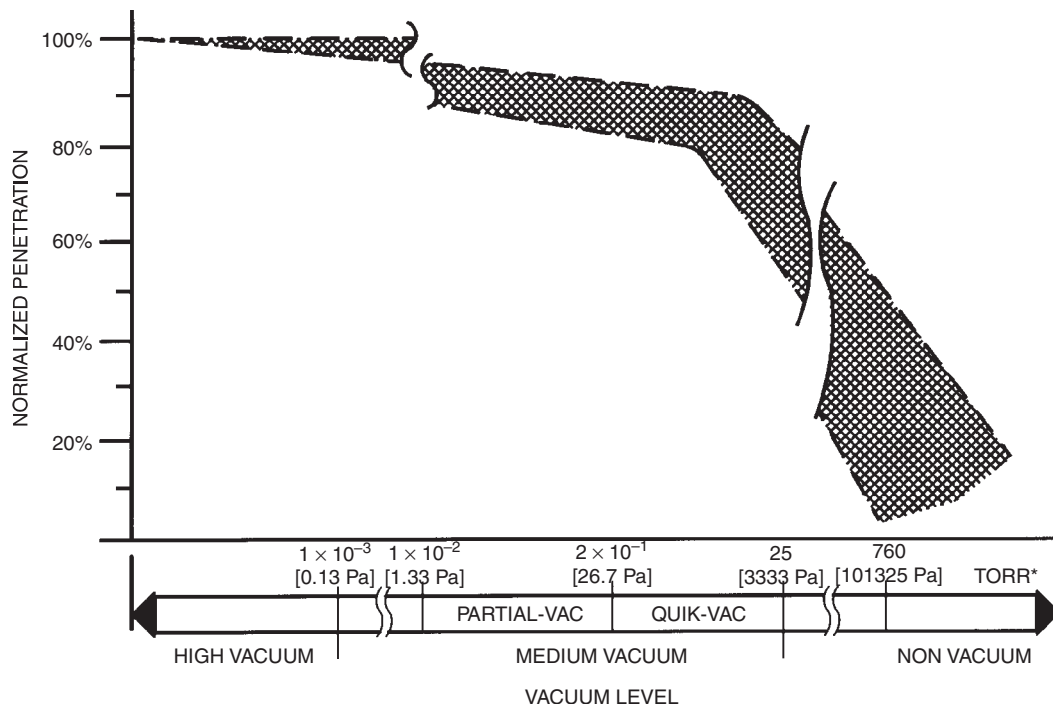
Figure 13—Mobile Gun Configuration

vacuum level any better than 1.3 Pa [1.0×10^{-2} torr]. In addition, the welding chamber can be custom designed to closely encompass the workpiece and any associated fixturing, thus minimizing the welding enclosure volume. These conditions allow evacuation times in the range of 3 seconds to 20 seconds to be achieved. High-production systems have been devised in which pumping times do not affect cycle times. In these systems, multiple workstations are employed with one station pumping while the other is welding.

6.2.3 Non-Vacuum Electron Beam Welding (EBW-NV). Another solution for reducing the cycle time needed for EBW is non-vacuum electron beam welding (EBW-NV). In this mode, welding is accomplished at approximately atmospheric pressure. EBW-NV requires that the beam generation and workpiece regions be isolated from each other by use of several vacuum dividers. Each vacuum zone in the series is evacuated with its own pumping system, allowing a different pressure to be formed between the gun and the workpiece. Pumping in this manner eliminates the need for vacuum exposure to the workpiece. The welding time required is then controlled by workpiece setup under the beam.

When either the EBW-MV or EBW-NV mode of operation is employed, some loss of penetration capability, compared to EBW-HV, is incurred. The magnitude of this loss in penetration capability can vary from as low as a few percent to as high as nearly 100% (see Figure 14). For example, at pressures on the order of 1.3 Pa [1.0×10^{-2} torr] both high- and low-voltage electron beams travel distances of 127 mm–254 mm [5 in–10 in] with only a minor loss in penetration capability, while at atmospheric pressure even high-voltage electron beams incur a substantial loss in penetration capability over a distance of only about 13 mm–25 mm [0.5 in–1 in].

An increase in pressure surrounding the workpiece increases the frequency that electrons in the beam collide with the residual gas molecules in the beam path. These collisions decrease the electron energy and expand the beam, resulting in loss of power and beam dispersion, reducing the specific power being delivered to the workpiece. The spread in the data



Note: A large drop in the penetration occurs at conditions approaching atmospheric. This is caused by the large number of interactions that electrons have with the ambient gas at these pressures.

*Refer to Annex A for cross reference of various pressure units.

Figure 14—Weld Penetration Versus Vacuum Level Chart

shown in Figure 14 indicates that operational parameters other than pressure (e.g., beam voltage, gun-to-work distance, residual gas, workpiece composition, etc.) impact the achievable weld penetration.

6.3 High- and Low-Voltage EBW Equipment. The beam voltages used for EBW cover a range from approximately 30 kV (where electrons are accelerated up to velocities near 35% of the speed of light) to approximately 200 kV (where electrons are accelerated to velocities near 70% of the speed of light). Traditionally, systems operating at beam voltages up to 60 kV are referred to as low-voltage EBW machines, while systems operating at beam voltages greater than 60 kV are referred to as high-voltage EBW machines.

Non-vacuum EBW machines are always high-voltage systems. High voltages maximize the working distance (usually length of beam travel in atmosphere). High-vacuum and partial vacuum EBW machines can be either high- or low-voltage systems and high power (30 kW) output levels are readily attainable in both, and each is regarded as having some general advantages. Some of the differences between the two systems are given below:

- (1) High-voltage beams can be focused to smaller spot sizes than low-voltage beams at equivalent power levels.
- (2) Low-voltage beams produce less energetic X-rays than high-voltage beams.
- (3) Low-voltage systems employ compact electron beam guns which can be manipulated through multiple axes within the work chamber.

Decisions on whether to use high-voltage or low-voltage machines should be made after careful evaluation of the specific advantages each method offers when applied to a particular task.

6.4 Components of the EBW System. 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.

6.4.1 Electron Beam Gun Column. The electron beam gun column allows the electron gun assembly to convert free electrons into a concentrated high power beam and direct the electron beam through space. A more detailed description of the electron gun assembly is found in 5.1.1.

The electron optics segment of the column assembly is comprised of a focus coil, which serves to constrict the electron beam to a tightly concentrated focal spot, and a set of deflection coils that are used to deflect the beam over the workpiece surface.

6.4.2 High-Voltage Power Supply. The high-voltage power supply is typically housed in an oil-filled tank. The same tank may also contain the beam current control (bias) and the cathode-heating (filament) power supplies. An associated control system serves to maintain the outputs of the power supplies at constant levels regardless of line voltage or load variations (within reasonable limits). Some power supplies incorporate fiber optics for control signals to achieve fast response times and electrical isolation. In addition, solid-state power supplies have been used as high-voltage power supplies in low-voltage EBW equipment.

6.4.3 Vacuum Pumping System. EBW-HV machines have either one or two vacuum pumping systems. The gun column and the work 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 the chamber is vented. Medium and non-vacuum machines typically use multiple pumping systems on the gun column to ensure a clean environment for the electron gun.

For the gun column, only a small capacity (either oil diffusion or turbo molecular) auxiliary-style vacuum pump is required to ensure a high vacuum level. A larger capacity vacuum pumping system is required for the welding enclosure. An oil diffusion, turbo molecular, or cryogenic pump backed by a mechanical booster pump assembly may be used to ensure that the welding enclosure is evacuated to the desired vacuum level in a reasonable time.

6.4.4 Weld Motion System. In order to fuse the entire length of a weld joint, the joint should be advanced under the beam, or, conversely, the beam should be advanced along the joint. EBW-HV and EBW-MV equipment manufacturers generally offer both fixed (externally mounted) and mobile (internally mounted) gun systems. EBW-HV and EBW-MV mobile gun systems are generally found on low-voltage machines, while fixed gun systems are found on high- or low-voltage machines. A fixed gun system can be expected to require a larger welding enclosure and longer pumping times than a mobile gun system. The larger enclosure provides added space for accommodating the workpiece travel while traversing the joint. EBW-NV systems are high-voltage units which employ either workpiece motion or a combination gun-workpiece motion to accomplish welding.

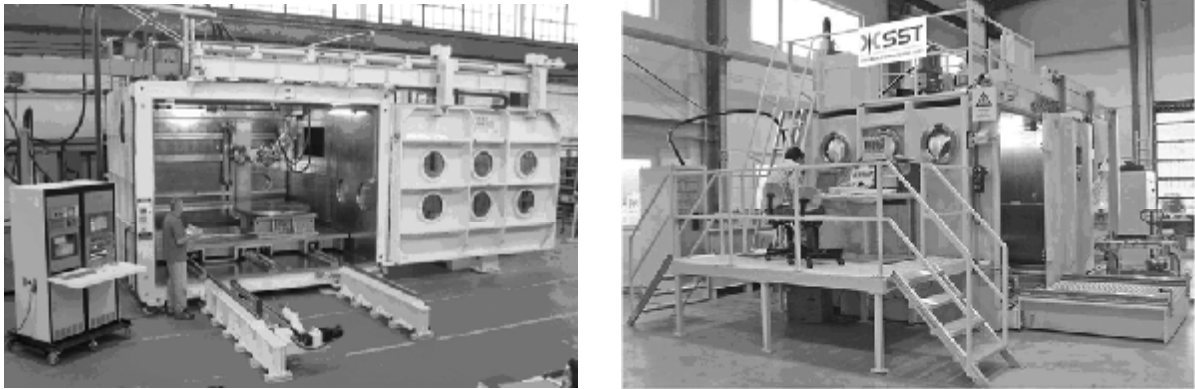


Figure 15—Large Chamber, High Vacuum and EBW Production Units

Figure 15 shows two EBW-HV mobile gun systems that have the capacity to provide up to 60 kW of beam power continuously and each system incorporates an industrial type CNC controller. The controller employed utilizes a specially developed executive software package that ensures all systems operation (workpiece motion, vacuum sequencing, beam generation, etc.) can be performed under either totally manual or fully automatic conditions. It also simultaneously ensures that all parameter setting/seam tracking/data logging functions are overseen in an automatic manner.

6.4.5 Welding Enclosures. In EBW-MV and EBW-HV, the welding enclosure provides an X-ray-tight vacuum box around the workpiece. Smaller enclosures are typical of medium vacuum machines dedicated to specific welding tasks where enclosure and tooling may be a single unit. Larger enclosures used for high- or medium-vacuum machines are designed for a variety of different welding tasks. For a non-vacuum machine, the welding enclosure need only be X-ray tight, since a vacuum environment is not required.

6.4.6 Seam Tracking. Seam-tracking equipment is available for all equipment marketed today and in many cases, can be retrofitted onto existing machines. 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 backscattered current is monitored as the beam is scanned on the workpiece, a change in backscattered current will be noted each time the beam crosses the joint.⁸ This technique can be used either prior to or during the actual welding process.

The beam is scanned normal to the joint path using the system's beam deflection capability. The level of backscatter current is monitored using an antenna at the entrance point of the beam into the work chamber (see Figure 16). The change in current is usually displayed on a monitor which has an enhanced spot showing the aligned beam position. As the joint is traversed, the table or gun is moved to bring the beam spot to the point of maximum inflection on the monitor. This technique can be used to program a joint for computer-controlled welding or to align a fixtured weld joint. For those systems where the gun is moved during the weld, this is the preferred method of beam alignment.

If a joint is too irregular or mismatched, the backscattering may not be clear enough for detection. On the other hand, if the part or faying surfaces are marked with scratches or burrs, the number of backscattered peaks may be too numerous to uniquely determine the joint. For these conditions, alternate alignment techniques such as video or direct viewing should be used. Vision systems that employ either gray-scale or laser scattered light tracking may be implemented to facilitate pre-scan or real time seam tracking. However, these alternate systems should be designed to handle the rigors of both vapor deposition and X-ray generation that are prevalent in an EBW chamber environment and should also be vacuum compatible.

⁸ Carroll, M. J. and D. E. Powers, 1985, Automatic Joint Tracking for CNC-Programmed Electron Beam Welding, *Welding Journal* 64(8): 34–38.

PRINCIPLE FOR SEAM FINDING AND TRACKING USING SECONDARY EMISSION

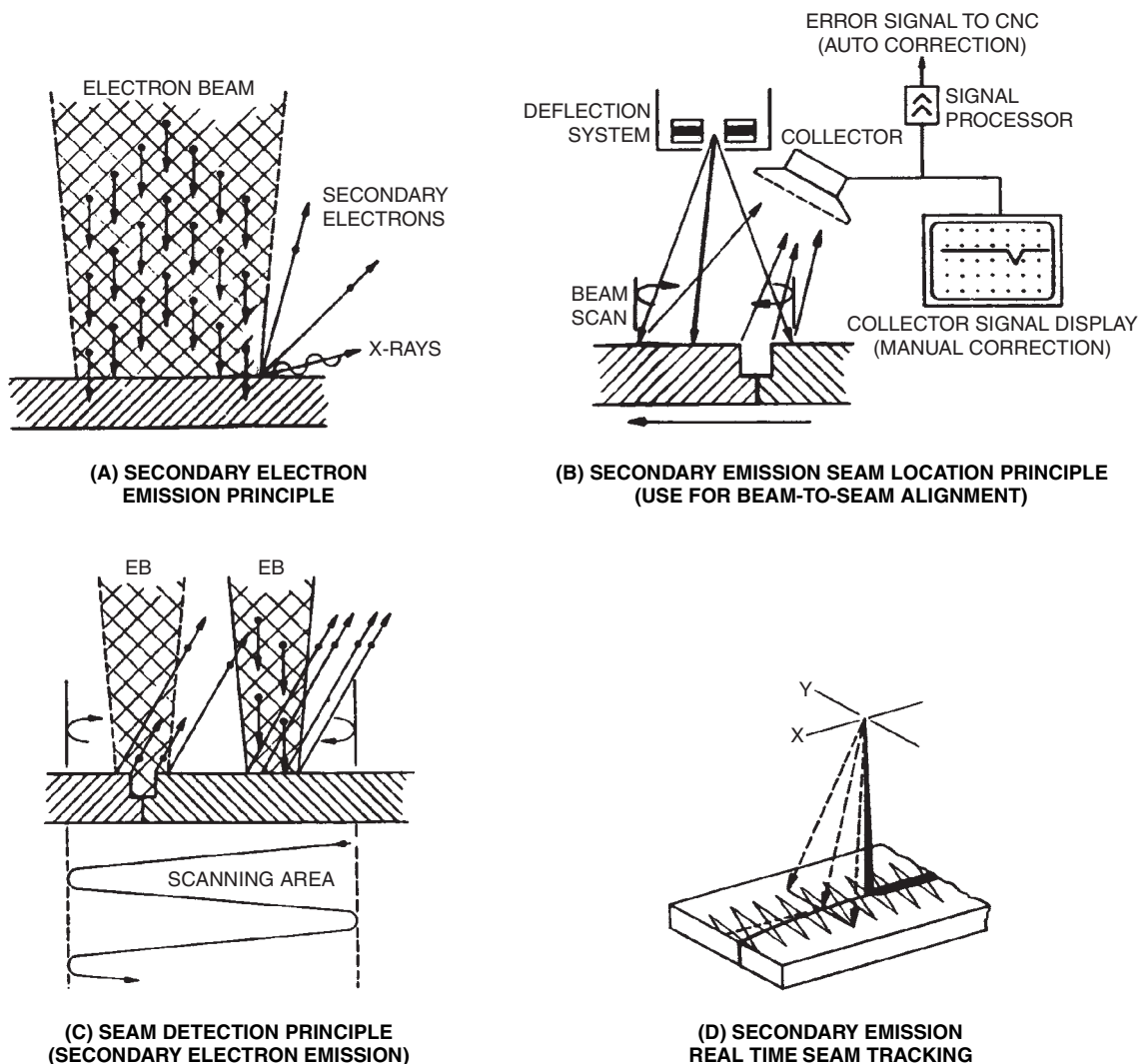


Figure 16—Overview of EB Seam Tracking Basics Using Secondary Emissions

In addition to providing the capacity for accomplishing on-line (“real time”) seam tracking in a fully automatic fashion, a feature that allows the joint seam ahead of the weld beam impingement point (during welding) to periodically be scanned—thereby producing a signal which the CNC unit can then use to automatically compensate for any probable beam-to-seam misalignment conditions that might result from possible seam run-out or stray magnetic through a high resolution viewing system provided on the unit. Figure 16 schematically defines the seam tracking system’s operational characteristics. Concurrent with providing a real time seam tracking and misalignment correction capability, the unit’s CNC system controls the following “axes” in a continuous interpolating fashion:

- (1) workpiece linear movements
- (2) workpiece rotary movements

- (3) beam current
- (4) beam deflection amplitudes
- (5) beam deflection frequencies
- (6) beam focus

CNC system controls also provide continuous monitoring of the programmed operational commands, indicating any functional faults detected by displaying an appropriate error message.

6.4.7 System Control Units. Modern EBW equipment is supplied with programmable logic control of the discrete (ON/OFF) sequencing functions and welding parameter analog inputs/outputs. Regulation of individual operating parameters is normally done with solid-state control units provided to ensure the parameters are continually maintained within one percent of the set value.

A beam-control module serves to turn the beam instantaneously ON/OFF (e.g., pulse the beam in either a repetitive or non-repetitive fashion) and vary (either up or down) the magnitude of beam current in a ramped or stepped fashion. Separate focus and deflection control modules may be employed to intermittently or continuously vary the plane in which the beam focal spot occurs, and may move this beam focal spot about in a dc (fixed) or ac (oscillatory) manner, or both.

CNC is optionally provided with software that allows part programs to be entered in a conventional CNC machine tool manner using individual parameter command controls or in a TEACH/LEARN fashion. Such CNC control units are industrial-type control systems. They have the ability to perform reliably under normal manufacturing environment conditions which are generally too hostile for conventional computers. For a view of a typical EBW industrial CNC operation control pendant and console, see Figure 17.



Figure 17—Electron Beam Welder CNC Pendant and Console

6.4.8 Video and Optical Viewing Systems. Video and optical viewing systems can provide a magnified view of the joint region allowing preweld inspection of the joint, monitoring during welding, and postweld inspection. While video viewing systems can allow record and playback capability, integral gun optics can provide a near co-axial view of the weld joint. Magnification can provide up to a 40X view of the weld joint allowing for a high resolution view of the joint before welding assuring joint fit-up, during welding to identify process disturbances, and after welding in order to examine the weld for surface irregularities or defects. Viewing of the joint during the weld allows for manual adjustment of the weld parameters, such as part position or focus, and for manual intervention for joint run-out or during repair welding. Manual adjustment of weld parameters, made while viewing a weld, can be useful during parameter development to optimize welding conditions, i.e., keyhole stability.

Bright joint illumination may be provided by bulb or nude filaments located within the gun column. Vapor shields are employed to protect the viewing optics from condensed weld vapors and are removable for cleaning or replacement. Viewing optic polarizers are also employed to reduce the intensity of light within the weld region to a comfortable level for the operator.

6.5 EBW System Function and Performance Control. Electron beam welding was first commercially employed during the late 1950s. Since that time, the continued application of the process to the performance of a variety of different production manufacturing tasks has resulted in an ongoing development to its present day capacity for being able to have these workpieces located either in or out of a vacuum environment.

When coupled with the continuing enhancement of the process controls, EBW can be easily adapted to a wide range of workpiece conditions and operating environments. Beam voltage and current regulation, fast response beam current level control, real time seam tracking, versatile beam deflection capacity, computer integrated workpiece motion and process operational control, process parameter monitoring, and data logging/malfunction capacity are just a few examples of the type of process control flexibility readily available with today's EBW equipment.

6.5.1 Power Supplies. Modern EBW systems generally employ high frequency ("switch-mode") type power supplies, instead of the older low frequency ("transformer-style") variety power supplies and primary steering (MG or SCR) units. These new switch-mode style units prevent uncontrolled "arc-outs" from occurring by sensing such a pending condition and reducing the high voltage until the pending arc-out potential is eliminated and then automatically restoring the high voltage to the proper operating level. These switch-mode power supplies utilize a fast response (low energy storage), high frequency (usually greater than 20 kilohertz) method of high voltage generation as well as the solid-state switching electronics needed for permitting the beam current and beam voltage to be monitored and impending arc-outs sensed and controlled.

6.5.2 Beam Diagnostics. Over the past decade, several diagnostic tools for characterizing electron beams have been developed and are available for commercial use. These beam probing techniques are primarily based on modifications to a traditional Faraday Cup and utilize direct measurements of the electron beam current to obtain a profile of the beam energy distribution as a function of time as the beam passes over an edge, slit, or pinhole. The resulting signal obtained as the beam passes over the edge or slit can provide information about the beam shape and size along with the power density. Using the data obtained with a given diagnostic system, estimations of the sharp focus setting, the beam diameter, the general beam profile, and the power density distribution can be made. This information can then be used to characterize the beam and verify that it meets the requirements set forth in the process and procedure specifications for a given weld. Figure 18 provides output from a simple diagnostic demonstrating the effects of changes in focus on the energy density of the beam.

Several diagnostic systems are commercially available and have been used in a number of development and manufacturing tasks. For example, diagnostic systems have been used to characterize and compare the performance of different welders,^{9,10} to transfer parameters from one welder to another,¹¹ and as a quality control tool.¹² Since these systems pro-

⁹ LaFlamme, G. R. and D. E. Powers, 1991, Diagnostic device quantifies, defines geometric characteristics of electron beams, *Welding Journal* 70(10): 33–40.

¹⁰ Palmer, T. A. and J. W. Elmer, 2007, Characterization of Electron Beams at Different Focus Settings and Work Distances in Multiple Welders Using the Enhanced Modified Faraday Cup, *Science and Technology of Welding and Joining*, 12(2), 161–174.

¹¹ Palmer, T. A., J. W. Elmer, K. D. Nicklas, and T. Mustaleski, 2007, Transferring Electron Beam Welding Parameters Using the Enhanced Modified Faraday Cup, *Welding Journal* 86(12): 388-s–398-s.

¹² Palmer, T. A. and J. W. Elmer, 2008, Improving Process Control in Electron Beam Welding Using the Enhanced Modified Faraday Cup, *Journal of Manufacturing Science and Engineering*, 130(4), 041008.

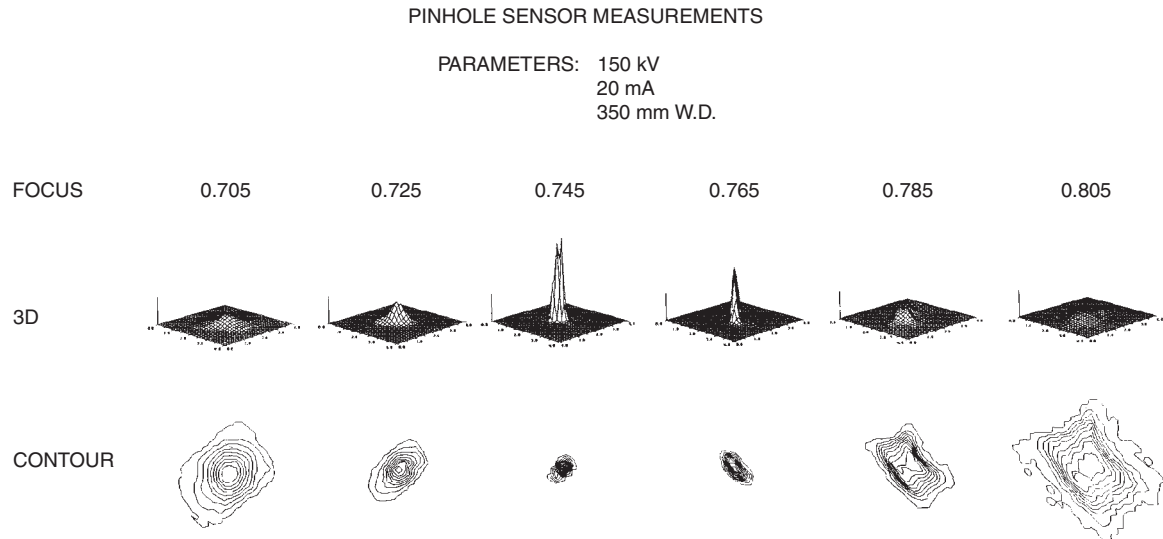


**Figure 18—Graphic Representation of the Energy Density Changes
an EB Experiences When Being Focused**

vide such detailed information about the performance of individual welders, they represent a useful tool for characterizing weld performance and can be integrated into research, development, and industrial operations.^{8–11}

6.5.3 Beam Deflection. In addition to high-speed beam deflection, which is defined as beam rastering, new variable frequency (low to high speed) programmable pattern generator deflection devices are being employed to provide a means for delivering energy in a discrete or continuous fashion to the workpiece in a precisely described manner (see Figure 19).¹³

With recent advances in deflection coil and deflection driver design technologies, extremely high (mega-hertz) beam deflection capabilities have provided EB users with the capacity to utilize a single beam to perform multiple tasks (welding/pre- and postweld treatment/etc.) at different locations in a seemingly simultaneous manner (see Figure 20). Experience has shown it brings some benefits. The explanations why it does so are rather speculative. In the case of a low-voltage but high power density (sharply focused) beam, it may move the process from the vaporization mode into the melting mode, reducing porosity in the welds by broadening the weld and keeping the weld puddle open longer, permitting better outgassing of the molten metal. With higher power beams it does not seem to be as important. In EBW-NV welding, it cannot be used and is not found to be necessary.

6.6 EBW Equipment Specification. See Annex B which is intended to provide a uniform means of specifying Electron Beam Welding equipment and thereby allows an objective and readily available comparison of function and performance of components and subsystems critical to the successful installation, operation, and maintenance of such equipment to be made.¹⁴

¹³ Farrell, W. J. and J. D. Ferrario, 1987, A computer-controlled, wide-bandwidth deflector system for electron beam welding and heat treating, *Welding Journal* 66(10): 41–49.

¹⁴ For a detailed description of EBW process specification, see AWS C7.3:1999, *Process Specification for Electron Beam Welding*, An American National Standard, Miami: American Welding Society.

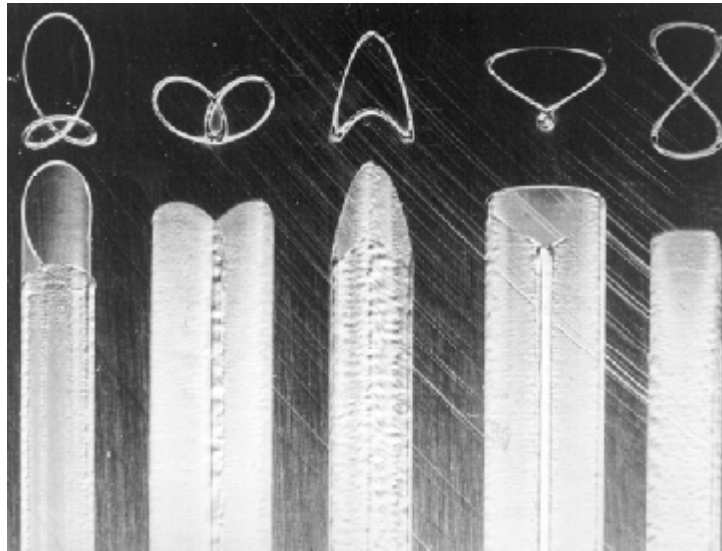
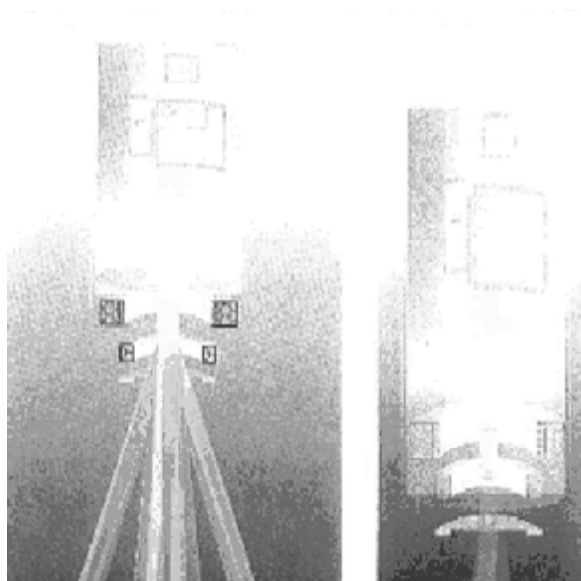
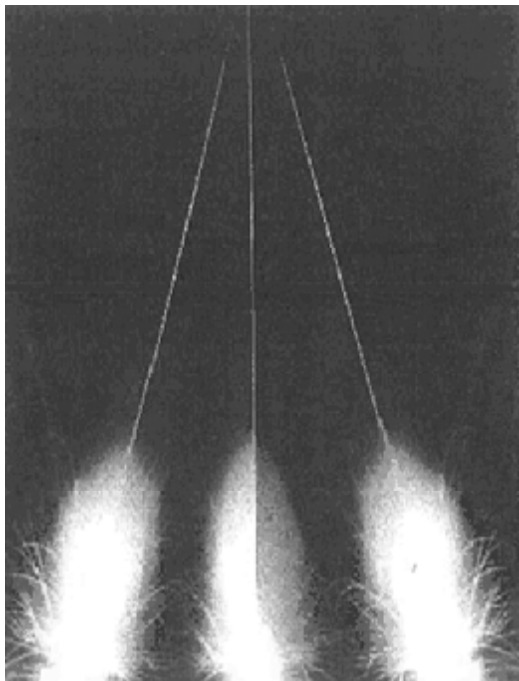


Photo courtesy of PTR—Precision Technologies, Incorporated

Figure 19—Examples of EB Deflection Patterns and the Effect Use of such Patterns has on Workpiece



Photos courtesy of Steigerwald Strahltechnik GmbH

Figure 20—Illustration of Simulated Multi-Beam EB Processing

7. Metallurgical Considerations

7.1 Introduction. Electron beam welds form as a result of the same metallurgical effects as other fusion welding processes. However, the high energy density of the electron beam welding process can produce weld shapes and defect morphologies quite different from conventional arc welds. The high intensity of the electron beam can allow the use of high travel speeds resulting in deep and narrow single pass welds which produce very rapid and localized heating and cooling. This rapid heating and cooling can influence the degree to which metallurgical processes affect the structure and properties of the weld fusion zone (FZ), heat-affected zone (HAZ), and base material (BM). Laser beam welding can produce similar metallurgical effects. In addition, the vacuum environment of EBW-HV can increase the occurrence of vaporization of lower melting point alloying additions and reduce the occurrence of hydrogen pick up due to contamination of filler metal or shield gases typical of other fusion processes.

The metallurgical effects, which can take place during welding include:

- (1) heat-affected zone
 - (a) annealing, solution annealing, recrystallization, and grain growth
 - (b) phase transformations, tempering, and age hardening
 - (c) liquation and hot cracking
 - (d) subsolidus cracking and base metal effects
- (2) fusion zone
 - (a) grain structure and orientation
 - (b) phase transformations
 - (c) segregation, precipitation, and cracking
 - (d) dissolution of gases, porosity formation

These metallurgical effects can produce structures and mechanical effects which influence weld properties such as strength, hardness, ductility, toughness and corrosion resistance, which can be significantly different than those of the base material, thus ultimately affecting weldment performance.

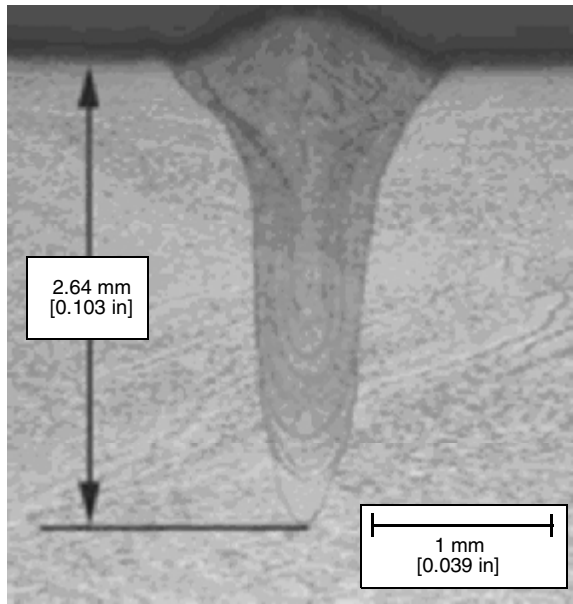
The nature of the EBW process, with its capacity for producing both a low-energy input and high aspect ratio weld, provides a distinct advantage in minimizing the amount of material affected by the welding process. A comparison between typical electron beam and GTA welds is shown in Figure 21 to illustrate this effect. Even with EBW-NV, the weld fusion zone and heat-affected zones are much narrower than with the GTAW process. There will be, however, a full range of temperatures from ambient to the melting temperature experienced as a result of the EB welding process.

Understanding the nature of the thermal effects associated with welding has become increasingly significant as more complex and sophisticated materials are designed and welded. These materials are frequently dependent on thermomechanical processing for their strength and toughness. The EBW process is frequently useful in taking full advantage of the mechanical properties of these materials because of the limited extent of the thermal effects.

In this section, general metallurgical effects are reviewed as well as some of the specific effects the EBW process has on various pure metals and alloys. The limited scope of this document prohibits a detailed treatment of each family of materials. The objective is to call attention to problem areas which should be further researched before proceeding. Such research is difficult with many alloys since little of a specific nature has been published relating to the EBW process. Literature associated with the metallurgical response to laser welding can be useful and extrapolating the data available from other fusion welding processes will help.

7.2 Heat-Affected Zone

7.2.1 Annealing—Solution Annealing—Recrystallization—Grain Growth. One commonly used means of strengthening a material is by work-hardening through cold-working operations, such as swaging, drawing, rolling, planishing, or peening. Strengthening also occurs when final hot-working operations are done at temperatures below the recrystallization temperature. Material hot worked in this fashion retains a part of the lattice strain and therefore is strengthened. Annealing of a material relieves these lattice strains by recovery and recrystallization, resulting in a



(A) ELECTRON BEAM WELD

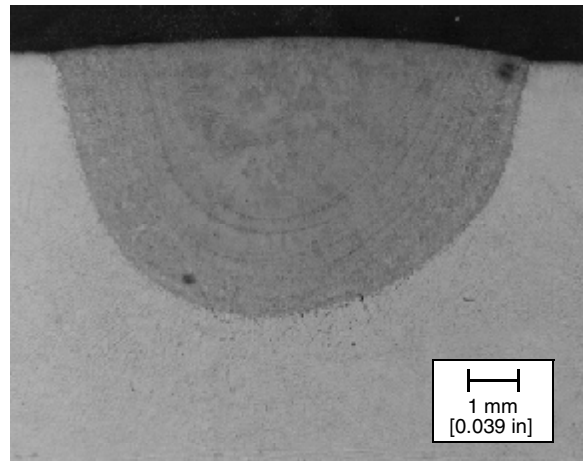


Photo courtesy of Los Alamos National Laboratory

(B) GAS TUNGSTEN ARC WELD

Source: Adapted from AWS Welding Journal, December 2007.¹⁵

Figure 21—Comparison of an Electron Beam Weld and Gas Tungsten Arc Weld Profiles

softer material with lower strength. Increasing the temperature above the recrystallization temperature results in grain growth. An example of recrystallization and grain growth in a TZM (Mo-0.5Ti-0.08Zr) electron beam weld is shown in Figure 22.

Materials are also strengthened by the precipitation of second phase particles in the microstructure. The second phase can have relatively large particles, such as the carbides in stainless steels, or fine particles generally irresolvable by light microscopy, such as gamma prime precipitates in the nickel-base alloys. Solution annealing causes these particles to go back into solution with the obvious loss of strengthening effect. An example of the dissolution of carbides in the fusion zone of a stainless steel electron beam weld is shown in Figure 23.

The distribution of carbides or other phases, or both, whether intergranular or intragranular, affects the corrosion resistance of certain materials in aggressive environments. Electron beam welding a material in the solution-annealed condition can lead to precipitation of the carbides in the heat-affected zone (HAZ) as in other welding processes. The EBW process is less prone to this type of problem than other fusion welding processes because of its rapid heating and cooling rates.

7.2.2 Transformations—Tempering—Age Hardening. The most familiar transformation for strengthening steels is the martensite transformation. For example, since carbon is far more soluble in steels at high temperature, rapid cooling results in the transformation of austenite to martensite, which is a supersaturated solid solution of carbon in iron. As-quenched martensite has a high strength but exhibits very little ductility. Reheating the martensite structure causes the carbon to precipitate as an iron carbide. This tempering of the martensite results in a reduction in strength and hardness and an increase in ductility.

¹⁵ T. A. Palmer, J. W. Elmer, K. D. Nicklas, and T. Mustaleski, 2007, Transferring Electron Beam Welding Parameters Using the Enhanced Modified Faraday Cup. *Welding Journal* 86(12): 397-s, Fig. 11(B).

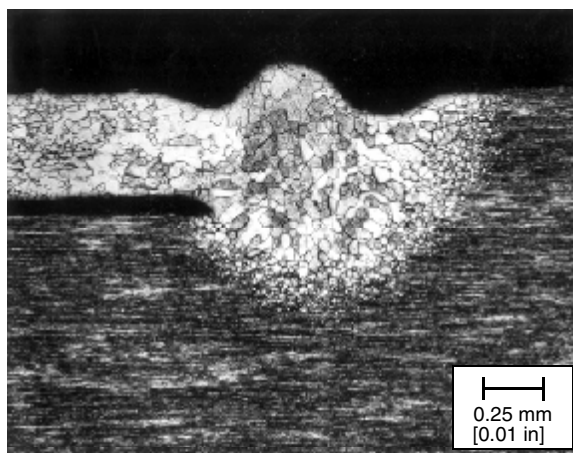


Figure 22—Longitudinal Cross Section of TZM Welded with Electron Beam Process showing Grain Growth in Weld Metal Zone and Epitaxial Solidification from Base Metal

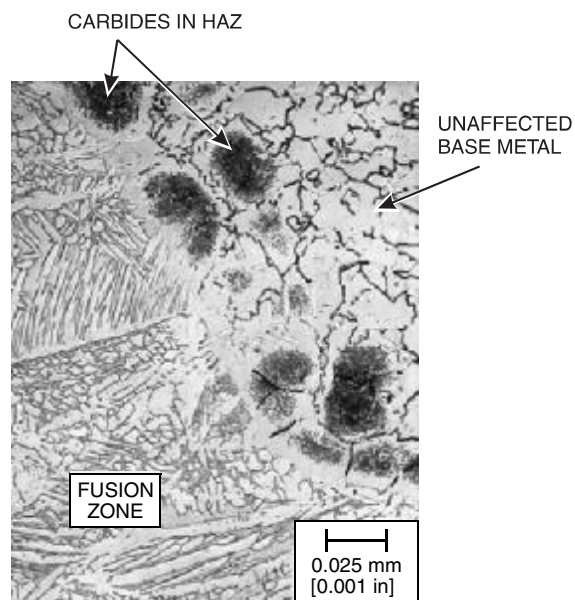


Figure 23—Cross Section of Stainless Steel showing the Dissolution of Carbides in the Fusion Zone