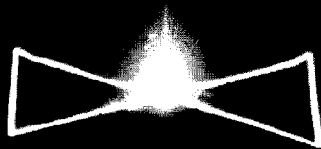


ANSI/AWS C7.1-92
An American National Standard

**Recommended
Practices for
Electron Beam
Welding**



American Welding Society

Keywords — Electron beam welding, high thermal conductivity materials, high-power density welding, recommended practices, refractory materials, thick-section welding, keyhole mode welding, deep-penetration welding, heavy-section welding

ANSI/AWS C7.1-92
An American National Standard

Approved by
American National Standards Institute
March 10, 1992

Recommended Practices

For

Electron Beam Welding

Prepared by
AWS High Energy Beam Welding and Cutting Committee

Under the Direction of
AWS Technical Activities Committee

Approved by
AWS Board of Directors

Abstract

This document presents recommended practices for electron beam welding. It is intended to cover common applications of the process. Process definitions, safe practices, general process requirements, and inspection criteria are provided.



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Foreword

(This Foreword is not a part of ANSI/AWS C7.1-92, *Recommended Practices for Electron Beam Welding*, but is included for information purposes only.)

Electron beam processing was initiated in the early 1900's, when an electron beam was used to produce tantalum metal by melting tantalum sponge. Since then, electron beam technology for material processing has steadily advanced.

While electron beam processing encompasses a wide range of metal processing activities, this document focuses on joining. The commercial application of electron beam welding (EBW) was first introduced in the late 1950's — and subsequently gained rapid and widespread acceptance by the industrial community. The process is known for its ability to provide high-aspect-ratio (depth-to-width) welds. In addition, it allows welding speeds on the order of 1800 in./min (760 mm/s) and single pass autogenous welds in metals of greater than 6 in. (150 mm) thickness to be achieved.

It is estimated that there are approximately 1200 electron beam welding machines presently in use in the United States and about the same number in use throughout the rest of the world - primarily in other industrialized countries such as the former Soviet Union, Japan, Germany, France and Great Britain. Of these machines, roughly 65% are high-vacuum units, 30% are medium-vacuum units, and 5% are nonvacuum units. The most common industries employing electron beam welding are aerospace, automotive, nuclear, and electronics/consumer products/medical/job shop.

The information contained in this *Recommended Practices* was compiled by the American Welding Society's C7B Subcommittee on Electron Beam Welding and Cutting by collecting information from various manufacturers and users of electron beam equipment. The information has, therefore, been carefully reviewed by a number of experts in the field of electron beam welding and should provide a helpful guide for use in applying the electron beam welding process.

However, it must be noted that the operating parameters specified in this recommended practices standard will not be the only possible parameter combinations that can be employed for successfully processing the materials and thicknesses shown. Changes in material chemistry, dimensional tolerances, machine calibration, etc. will cause changes in the resulting welds. Therefore, the procedures contained herein are being offered simply as a guide and are intended only for use in helping to make the job of applying the technology of electron beam welding easier and the application of the process more consistent.

Comments and suggestions for improvement of this Standard are welcome. They should be sent to the Secretary, Committee on High Energy Beam Welding and Cutting, American Welding Society, 550 N.W. LeJeune Rd., P.O. Box 351040, Miami, FL, 33135.

Requests for official interpretations of this Standard should be directed to the Director, Technical Standards and Publications, American Welding Society.

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Recommended Practices For Electron Beam Welding

1. Scope

These recommended practices present a description of electron beam welding equipment and procedures for welding a wide range of metals and thicknesses. The appropriate terms, definitions, and safety considerations are presented in detail. Information is included on designing for electron beam welding (EBW), welding dissimilar metals and thicknesses, fixturing, specifications, and operator training and qualifications.

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. Related processes such as EB cutting, EB heat treating, and EB curing, though similar in nature and procedure, were also considered beyond the scope of this publication.

2. Glossary

The following glossary contains terms and definitions that are generally specific to the EBW process. Terms that are not part of common welding vocabulary are defined and the definitions of some standard welding terms are changed slightly to more accurately describe those terms as they pertain to the EBW process. General terms pertaining to all welding processes are not listed in this compilation but can be found in the ANSI/AWS A3.0, *Standard Welding Terms and Definitions*.

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.

aspect ratio. The ratio of the depth of fusion to the width of weld.

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

beam deflection. Movement of the electron beam by electromagnetic coils or by undesirable spurious magnetic or electric fields. This movement, when intentionally induced by a direct or alternating current applied to the deflection coils, results in a simple offset of the beam from its normal position (DC), or a continuous oscillatory movement (AC).

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).

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, is

$$P = VI \quad (\text{Eq. 1})$$

where

V = Beam Voltage, kilovolts

I = Beam Current, milliamperes

beam spot. Apparent size of the beam impingement area on the surface of the workpiece (working spot size as opposed to focal spot: see *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 called *grid cup*.)
- cathode.** The source of the electrons, commonly a filament 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.
- CNC.** An acronym for *Computerized Numerical Control*.
- cold shut.** A form of weld discontinuity caused by material solidifying at an interface before that interface unites to form a continuous structure.
- column valve.** A vacuum valve between the electron gun and the workchamber used to preserve vacuum and prevent contamination of the gun when the chamber is vented. (Also called *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 **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.
- 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 gun.** A device for producing, accelerating, and forming a directed stream of electrons. See **diode** 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, nonvacuum**.
- electron beam welding, high vacuum (EBW-HV).** An electron beam welding process mode in which welding is accomplished at a pressure of 10^{-6} to 10^{-3} torr (approximately 10^{-4} to 10^{-1} pascal).
- electron beam welding, medium vacuum (EBW-MV).** An electron beam welding process mode in which welding is accomplished at a pressure of 10^{-3} to 25 torr (approximately 10^{-1} to 3×10^3 pascal).
- electron beam welding, nonvacuum (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. The 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 **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*.)
- focal spot.** Location where the electron beam has the smallest cross-sectional area. (Also referred to as *sharp focus* or *focal point*. See **beam spot**.)
- focus.** Converging an electron beam to form a focal spot using electromagnetic or electrostatic forces. (See **focus coil**.)
- focus block.** See **target**.
- focus 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 kilowatts per square centimeter. (See **electron beam welding and specific power**.)

high voltage electron beam. A relative term, normally used to identify electron beam equipment employing a beam voltage in excess of 60 kilovolts. See **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 hole surrounded by molten material that penetrates deeply into or through the workpiece. As the concentrated heat source is advanced, molten material flowing around the walls of this 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 kilovolts or less. See **beam voltage** and **high voltage electron beam**.

mobile gun. Electron beam gun that may be moved about within the welding chamber and typically operates at 60 kV or below.

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 vapor pressure greater than the surrounding environment and evaporates. See **virtual leak**.

overpowering. Using more beam power than is required for 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 welding vacuum 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 are 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.

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.

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

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 post weld inspection.

3. Safety Considerations

3.1 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 chapter 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/ASC Z49.1, *Safety in Welding and Cutting*, nor all the OSHA regulations established to protect personnel working on (or around) various forms of industrial machinery and vacuum equipment. The general requirements outlined in both these documents should be strictly adhered to at all times.

3.2 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

3.2.1 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 specification ANSI-C1, *National Electrical Code* (with primary reference to Article 660) and in accordance with the Joint Industrial Council specification JIC-EGP.1, *Electrical Standards for General Purpose Machine Tools*.

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 must 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 must be used to ensure complete discharge of all components. This grounding probe must 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-Z53.1, *Safety Color Code for Marking Physical Hazards*, and ANSI-Z35.1, *Specifications for Accident Prevention Signs*.

3.2.2 X-Radiation. X-radiation is produced when electrons collide with a substance (such as gas or metal). In the case of electron beam equipment, the majority of x-rays are produced when the beam impinges upon the workpiece. Lower levels are produced when the beam strikes gas molecules or other substances along the beam path to the workpiece. The intensity of the x-rays produced increases with increasing beam voltage, beam current, and the atomic number of the material being 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, the electron beam gun column, and the work chamber. X-rays are also 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-N543, *General Safety Standards for Installations Using Non-Medical 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 safety 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.

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.

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 (again, 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 feedthrough 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. 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 measurements taken is also strongly dependent on the type of instrument (energy range capability) and sweep rate (meter response time) employed. Radiation surveys should, therefore, always be carried out only by personnel properly trained to do such surveys.

Several standards exist for classification of radiation installations, and 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 in-

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 _____ (cm) from the machine's exterior surfaces.

Additional Comments (if required): _____

Figure 1 — Sample Form for Radiation Survey

Table 1
Radiation Exposure Standards

The following provides a guide to the maximum permissible survey instrument safe reading allowable (as interpreted from NBS Handbook 114, issued February 1975), expressed in milliroentgen per hour* (mR/h). The milliroentgen per hour is the unit of measurement registered by the readout scale on most radiation survey instruments.

Controlled Area — limited occupancy (area under supervision, length and frequency of exposure are controlled)	2 mR/h (Max., at 5 cm from outside surface of shielding)
Controlled Area — continuous occupancy (area under supervision, length and frequency of exposure not controlled)	0.5 mR/h (Max., at 5 cm from outside surface of shielding)
Uncontrolled Area — continuous occupancy (area not supervised, and no control over length or frequency of exposure)	0.2 mR/h (Max., at 5 cm from outside surface of shielding)

* NBS maximum values are actually given as maximum permissible dose equivalent values in rem per year [where a rem (radiation equivalent man) can, for all practical purposes, be considered essentially equal to a roentgen when dealing with x-rays], and per-hour maximum safe readings listed here are calculated on the basis of a 2500 working hour year (48 hours/week for 52 weeks) from those dose equivalent values. In all cases, when a lower radiation level than that specified here is reasonably achievable, that lower level should be employed to minimize the cumulative exposure of personnel.

stallation and should abide strictly by those regulations and standards.

3.2.3 Fumes and Gases. Toxic fumes and gases may be generated by electron beam equipment. Specifically, ozone (O₃), various oxides of nitrogen (NO and NO₂ in particular), and workpiece material fumes are generated by nonvacuum and medium-vacuum equipment in sufficient quantities to be harmful.

Therefore, 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 nonvacuum and medium-vacuum welding, personnel should not be allowed to enter the workpiece enclosure after welding until concentra-

tions 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 and Cutting*. Before welding any unfamiliar material, the Material Safety Data Sheet (MSDS) should be read to determine whether 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*. 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.

Extra 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.

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

Light emitted during EBW is produced by radiation from the molten metal in the weld pool. The intensity of radiated light increases with increased temperature of the metal. Therefore, since the visible light emitted during welding on high melting-point materials is too bright for direct viewing, special care must 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-Z87.1, *Occupational and Educational Eye and Face Protection*. All persons involved with EBW equipment should be instructed in the use of proper optical filtering and should be required to use such protection.

3.2.5 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 the American Vacuum Society in its *Vacuum Hazards Manual*.

3.3 References. The following codes, standards, specifications, books, and reports either have been cited in these recommendations or contain information that is useful. These references are included only as a source of helpful information.

Electrical Shock

(1) National Fire Protection Association (NFPA). *Electrical standard for metal working machine tools*, NFPA No. 79. Quincy, MA: National Fire Protection Association.

(2) ———. *National electrical code*, NFPA No. 70. Quincy, MA: National Fire Protection Association.

(3) Joint Industrial Council. *Electrical standards for general-purpose tools*, EGP-1. McLean, VA: Joint Industrial Council.

Fumes and Gases

(1) Hauser, Misler, Monroe, and Martin. *Electron beam welding of beryllium*. Dayton, Ohio: Air Force Materials Laboratory, WPAFB.

(2) Superintendent of Documents. "Occupational safety and health standards — air contaminants." *Code of Federal Regulations*, title 29, chapter 17, part 1910-section 1000. Washington, DC: U.S. Government Printing Office.

General

(1) American Institute of Physics. "Introduction to electron beam technology." *AVS Vacuum Hazards Manual*. New York, NY: R. Bakish, John Wiley and Sons, 1974.

(2) American National Standards Institute. *Occupational and educational eye and face protection*, ANSI Z87.1. New York, NY: American National Standards Institute.

(3) ———. *Safety color code for marking physical hazards*, ANSI Z53.1. New York, NY: American National Standards Institute.

(4) ———. *Safety in welding and cutting*, ANSI Z49.1. New York, NY: American National Standards Institute.

(5) ———. *Specifications for accident prevention signs*, ANSI Z35.1. New York, NY: American National Standards Institute.

(6) American Welding Society. *The welding environment*. Miami, Florida: American Welding Society, 1973.

Radiation

(1) Superintendent of Documents. *Federal supply contracts safety and health standards — ionizing ra-*

diation, title 41, chapter 50, part 204, section 20. Washington, DC: U.S. Government Printing Office.

(2) ——. *Occupational safety and health standards — ionizing radiation*, title 29, chapter 17, part 1910, section 96. Washington, DC: U.S. government Printing Office.

(3) ——. *Standards of protection against radiation*, title 10, chapter 1, part 20. Washington, DC: U.S. Government Printing Office.

(4) National Institute of Standards and Technology (NIST). *General safety standard for installations using non-medical x-ray and sealed gamma-ray sources, energies up to 10 MeV*, NBS Handbook 114. Gaithersburg, MD: National Institute of Standards and Technology.

(5) National Committee on Radiation Protection and Measurements (NCRP). *Basic radiation protection criteria*, NCRP Report No. 39. Ronald Press Company.

(6) ——. *Nondestructive testing handbook*, Vol. 1. New York, NY: Ronald Press Company.

(7) ——. *Medical x-ray and gamma-ray protection for energies up to 10 MeV, equipment design and use*, NCRP Report No. 33. New York, NY: Ronald Press Company.

(8) ——. *Structural shielding design and evaluation for medical use of x-rays and gamma-rays of energies up to 10 MeV*, NCRP Report No. 49. New York, NY: Ronald Press Company.

4. Process Fundamentals

4.1 Description of Process

4.1.1 Formation of an Electron Beam. This section briefly describes the “electron source” of the electron beam welding process, i.e., the electron beam gun. For a more detailed discussion the reader is directed to 4.3, Reference (1).

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” of the filament. As the temperature is increased, more electrons are emitted from the cathode until a maximum emission level is reached. This level, called *space charge limited emission*, occurs when a cloud of electrons that repels further emission from the filament is formed. In a triode gun (Figure 2), this cloud of electrons is shaped into a beam by an electrostatic field created by an appropriately shaped and charged bias cup and a positively charged anode. The combination

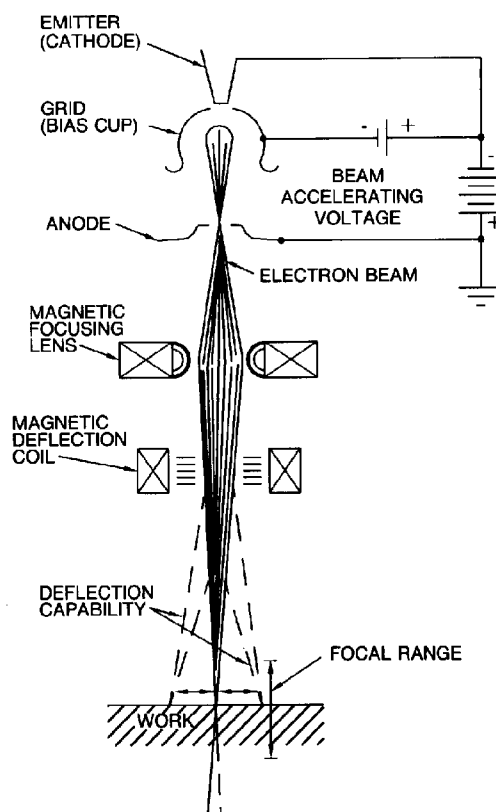


Figure 2 — Simplified Representation of an Electron Beam Gun Column

of all three of these components constitutes an electron beam gun.

In a diode gun, the bias cup and the emitter are at the same electrical potential and are referred to as the *cathode*. In a triode gun, the cathode is at one potential while the potential (bias) between it and the bias cup is varied to control the beam current. At a large negative bias, electron flow is inhibited, and the beam current is zero. As the value of the negative bias is reduced, electron flow increases. Both gun designs pass electrons through an anode at ground potential to accelerate them. 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.

4.1.2 Control of the Electron Beam. Since electrons are charged particles, their direction of travel can be controlled by the use of electromagnetic

fields. Thus, when the accelerated beam of electrons emerges from the aperture in the anode and begins to diverge (because of mutual repulsion and other causes), a focusing coil located below the anode can be used to counteract this divergence. By simply varying the current applied through this coil the electron beam can be focused at a desired location beyond the plane of the coil.

Deflection coils can be added below the focus coil to cause the beam to move to predetermined locations. Modern welding systems usually include a function generator or programmable deflection module to power the deflection coils providing a versatile control of beam movement.

4.1.3 Weld Formation. Numerous studies have been conducted to determine exactly how the weld is formed by the electron beam striking the work. The high energy density of the focused beam vaporizes some of the material on which it impinges. A keyhole forms in an equilibrium condition between the pressure of this expanding vapor and the surface tension of the molten material on the wall. As the beam traverses over the base metal, the material is melted at the leading edge of the keyhole, flows around the keyhole, and solidifies at the trailing edge.

The formation of the keyhole in high power density EBW provides the unique capability for deep, narrow welds and narrow heat-affected zones resulting in minimized distortion of weldments. This type of melting is referred to as *keyhole mode welding*. However, 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, irregular penetration (spiking) in the finished welds, or all three.

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*.

4.1.4 Welding Variables. In EBW, the primary welding parameters are beam voltage, beam current, travel speed, and focus coil current. The secondary variables are vacuum level, 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 much lower energy input can be used to give equivalent penetration with EBW than with conventional arc and laser beam welding processes.

Although the high power densities achievable can be a powerful tool for EBW, precise control of

these high power densities 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 welding parameters (accelerating voltage, beam current, focus coil current, and travel speed) appear to be remaining the same. Consequently, in critical applications, care must be taken to ensure filament installation, chamber pressure, beam deflection, and gun-to-work distance are maintained the same.

4.2 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.

4.2.1 The following are some advantages of EBW.

(1) The focused electron beam results in a very high energy density at the spot where the beam strikes the work. It is possible to concentrate the incident beam into a very small area, maximum-energy densities are about 100 to 1000 times higher than arc welding heat sources.

(2) Because of the high energy density, the total energy input is relatively low. This 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.

(3) High-aspect-ratio welds may allow single-pass welding where arc welding would require multipass 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 a wide range of applications with a single welding machine.

4.2.2 The following are some limitations of EBW.

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

(2) 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) Personnel must be protected from x-rays generated by the electron beam and equipment must be monitored periodically.

(5) Because the electron beam is deflected by magnetic fields, some dissimilar material combinations are difficult to weld. Ferromagnetic materials cannot be welded without careful degaussing. Fixturing must also be made from nonmagnetic materials.

(6) In high power density welding, weld discontinuities such as cold shuts and spiking, associated with root porosity, may develop. These discontinu-

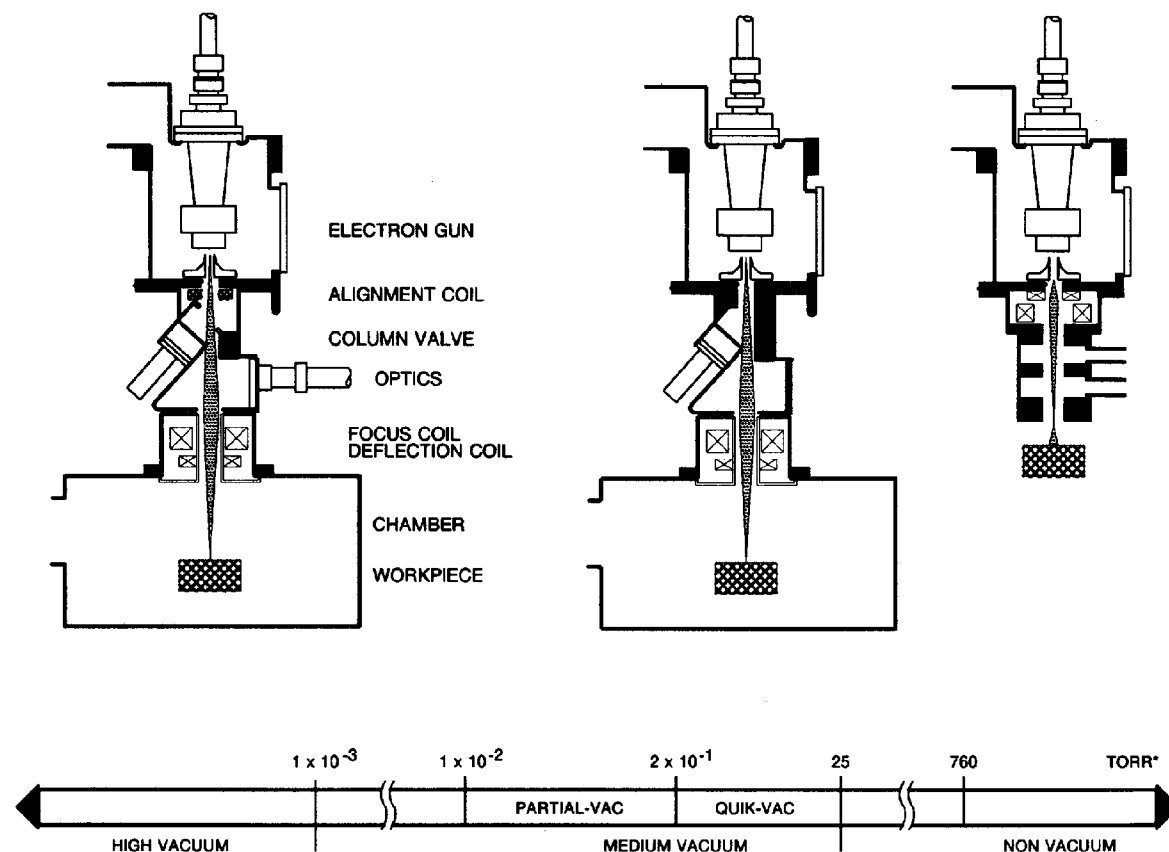
ities are particularly prevalent in partial penetration welds.

4.3 Reference

(1) American Welding Society. *Welding handbook*, Volume 2, Eighth Edition. Miami, FL: American Welding Society.

5. Description of Equipment

5.1 Introduction. Electron beam processing can be performed both in and out of vacuum (see Figure 3), utilizing fixed or mobile guns (see Figure 4), high- or low-beam voltages, etc. This section describes the three modes of EBW, high and low voltage machines, and components making up an EBW system.



*Refer to Appendix A for Cross Reference of Various Pressure Units.

Figure 3 — Electron Beam Modes of Operation

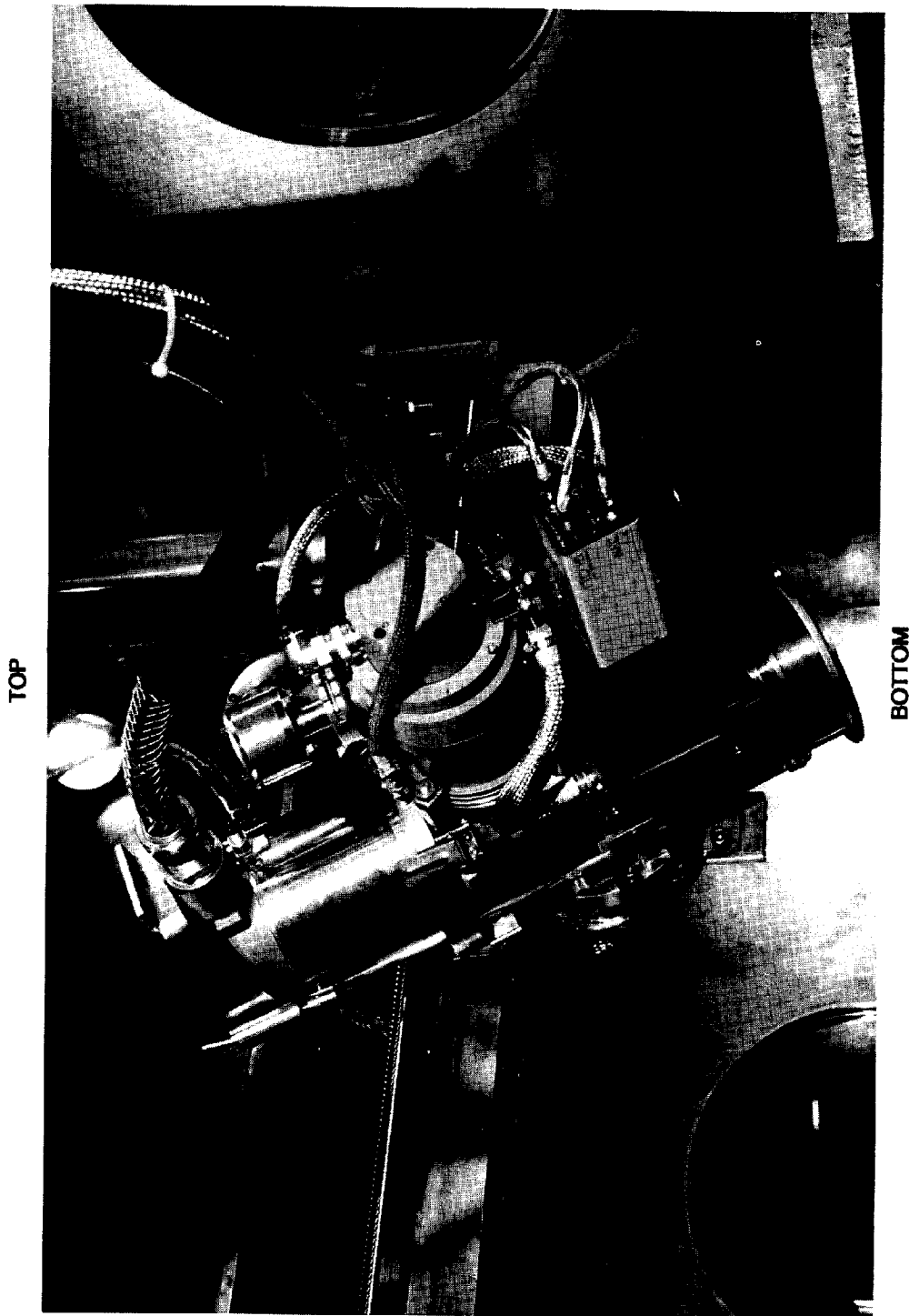


Figure 4 — Mobile Gun Configuration

5.2 Modes of Electron Beam Welding. The level of vacuum in which welding takes place determines the process mode (variation), and therefore, the type of equipment required.

5.2.1 High Vacuum Electron Beam Welding (EBW-HV) [10^{-3} torr (1.33×10^{-1} pascal) or lower]. When the electron beam was initially employed for production joining of materials, welding had to be performed in exactly the same environment needed for beam generation, i.e., an ambient vacuum of 10^{-3} torr (1.33×10^{-1} pascal 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 provide 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.

5.2.2 Medium Vacuum Electron Beam Welding (EBW-MV) [25 to 10^{-3} torr/3.33 x 10^{-1} to 1.33×10^{-1} pascal]. One means devised for reducing the required evacuation time is the use of medium-vacuum mode of 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 10^{-3} to 10^{-1} torr (1.33×10^{-1} to 13 pascal).

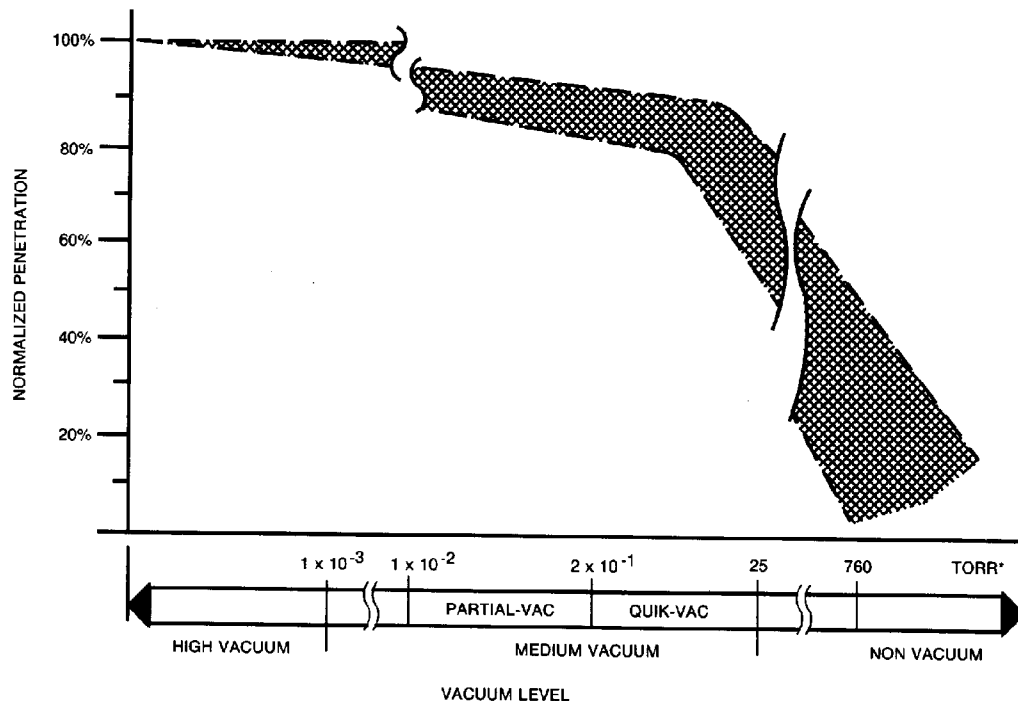
This mode of EBW requires that the beam generation and workpiece regions be isolated from each other by use of a vacuum divider (an aperture sized to impede gas flow without restricting beam passage). The two individual vacuum zones produced by employing a vacuum divider must be evacuated by separate 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 vacuum level any better than 10^{-2} torr (1.33 pascal). 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 to 20 seconds to be

achieved. High-production systems have been devised in which pumping time does not enter into the cycle time. This is achieved by employing multiple workstations and pumping on some while simultaneously welding in others.

5.2.3 Nonvacuum Electron Beam Welding (EBW-NV). Another solution for reducing the cycle time needed for EBW has been the development of nonvacuum electron beam welding (EBW-NV). In this mode, welding is accomplished at approximately atmospheric pressure. This mode of EBW requires that the beam generation and workpiece regions be isolated from each other by the use of several vacuum dividers. Each vacuum zone in the series is evacuated with its own pumping system, allowing a differential pressure to be formed between the gun and the workpiece. Pumping in this manner eliminates the need for vacuum exposure of 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 in 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 one hundred percent (Figure 5). Loss in penetration is due to the fact that as the pressure surrounding the workpiece is increased, the frequency that electrons in the beam collide with the residual gas molecules in the beam's path also increases. These collisions decrease the electron's energy and expand the beam. This results in power loss and beam dispersion, reducing the specific power being delivered to the workpiece. Figure 5 is representative of how penetration decreases with increasing pressure. In this graph, penetration data are normalized for comparison to weld penetration under high-vacuum conditions. The spread shown indicates that operational parameters other than pressure (i.e., beam voltage, gun-to-work distance, residual gas, workpiece composition, etc.) impact the achievable weld penetration.

For example, at pressures on the order of 10^{-2} torr (1.33 pascal) both high and low voltage electron beams travel distances of 5 to 10 in. (127 to 154 mm) 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 0.5 to 1 in. (13 to 25 mm).



(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 Appendix A for Cross-Reference of Various Pressure Units

Figure 5 — Weld Penetration Versus Vacuum Level Chart

5.3 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 of 60kV or less are referred to as *low voltage EBW machines*, while systems operating at beam voltages greater than 60kV are referred to as *high voltage EBW machines*.

Nonvacuum EBW machines are always high voltage systems. This maximizes the working distance (usable length of beam travel in atmosphere) capability. High-vacuum and partial-vacuum EBW machines are generally provided as both high and low voltage systems.

High-power (30 kW to 100 kW) output levels are readily attainable with both high and low voltage EBW systems, and each is regarded as having some

general advantages. The following are some of the comparative differences cited:

(1) High voltage beams can be focused to a smaller spot size 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.

5.4 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 other subsystems are avail-

able on many machines, seam tracking and programmable system controls.

5.4.1 Electron Beam Gun Column. The electron beam gun column allows the electron beam gun to produce free electrons, form these electrons into a concentrated high-power beam, and direct the electron beam through space. A more detailed description of the electron beam gun is found in 4.1.1.

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

5.4.2 High-Voltage Power Supply. The high-voltage power supply is housed in an oil-filled tank. The same tank also contains the beam current control and the cathode heating-power supplies. An associated control system serves to maintain the outputs of the power-supplies constant regardless of line voltage or load variations (within reasonable limits). Some power supplies incorporate fiber optics for control signals to achieve fast response times and electrical isolation.

5.4.3 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 nonvacuum machines typically use multiple pumping systems on the gun column to ensure a clean environment for the electron beam gun.

For the gun column, only a small capacity (either oil diffusion or turbomolecular) auxiliary-style vacuum pump is required to ensure the high-vacuum level required. A larger capacity vacuum pumping system is required for the welding enclosure. An oil diffusion, turbomolecular, or cryogenic pump backed by a mechanical booster pump assembly may be used. This ensures the welding enclosure is evacuated to the desired vacuum level in a reasonable time. Although more expensive than equivalent capacity oil diffusion pumps, turbomolecular and cryogenic pumps have been employed in place of oil diffusion pumps because of their compactness and their ability to eliminate

any possibility of oil backstreaming from the high-vacuum pumps.

5.4.4 Weld Motion System. In order to fuse the entire length of a weld joint, the joint must be advanced under the beam, or, conversely, the beam must be advanced along the joint. EBW-HV and EBW-MV equipment manufacturers generally offer both external gun and mobile gun systems. EBW-HV and EBW-MV mobile gun systems are generally found on low voltage machines. EBW-HV and EBW-MV 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.

5.4.5 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 doing a variety of different welding tasks. For a nonvacuum machine, the welding enclosure need only be x-ray tight, since the workpiece does not have to be put in any form of a vacuum environment.

5.4.6 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, a change in backscattered current will be noted each time the beam crosses the joint. 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. The change in current is usually displayed on a CRT (cathode ray tube) screen

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 CRT. 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 must be 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.

5.4.7 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 (i.e., pulse the beam in either a repetitive or nonrepetitive 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 system control is optionally provided with software that allows part programs to be entered in conventional CNC machine tool manner, individual parameter command controls, or 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.

6. Metallurgical Considerations

6.1 Introduction. In spite of its unique characteristics, the EBW process produces the same metallurgical effects as other fusion welding processes. Base-metal effects include annealing, solution an-

nealing, recrystallization, grain growth, phase transformations, tempering, aging, precipitation reactions, and, under some conditions, base-metal cracking. The fusion zone is characterized by epitaxial solidification and microstructures typical of other fusion welding processes. The fusion zone of some materials may exhibit susceptibility to porosity and cracking.

The grain size of the weld and heat-affected zone are significantly finer with EBW compared to arc welding processes. This is due to the rapid heating and cooling characteristics of the EBW process. The finer grain size results in improved toughness.

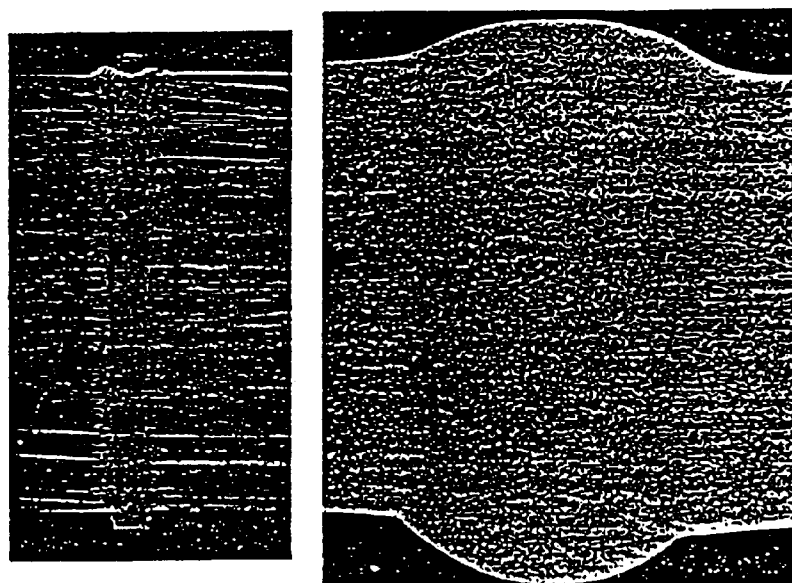
The nature of the EBW process, with its low-energy input and high aspect ratio provides a distinct advantage in minimizing the amount of material affected by the welding thermal cycle. The comparison between electron beam and GTA welds seen in Figure 6 illustrates this effect. Even with EBW-NV, the weld 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 weld.

Understanding the nature of the thermal effects associated with welding has become increasingly significant as more complex and sophisticated materials are welded. These materials are frequently dependent on thermo-mechanical 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 of the process.

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 has been published of a specific nature relating to the EBW process. Many times the only choice is to extrapolate the data available from other fusion welding processes. Further information can be found in the suggested reading list shown at the end of Section 6

6.2 Heat-Affected Zone

6.2.1 Annealing — Solution Annealing — Recrystallization — Grain Growth. One commonly



Welding Conditions (1/2 Inch Thick, Type 2219 Al Alloy)

	Electron Beam Weld	Gas Tungsten Arc Weld		
		1st Pass ^a	2nd Pass ^b	Total
Voltage, V	30×10^3	11.7	13.0	...
Current, A	200×10^{-3}	270.	270.	...
Welding speed, in./min	95	6.5	7.5	...
Power, kW	6	3.2	3.5	6.7
Energy, kJ/in.	3.8	29.6	28.0	57.6

a. Without wire

b. With 0.062 in dia. Type 2319 Al filler metal

Figure 6 — Comparison of EB and GTA Weld Profiles

used means of strengthening a material is by work-hardening. This can be in the form of cold work 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. This results in the material being softer and having 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 7.

Materials are also strengthened by the precipitation of second phase particles in the microstructure. The second phase has relatively large particles, such as the carbides in stainless steels, or fine particles generally unresolvable 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 solutioning of the carbides in a stainless steel electron beam weld is shown in Figure 7.

The distribution of carbides or other phases, or

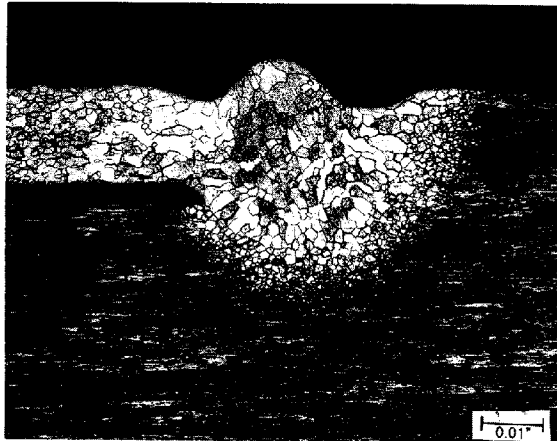


Figure 7 — Cross Section of TZM Welded with EB Process Showing Grain Growth in Fusion Zone and Epitaxial Solidification from Base Metal

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 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.

6.2.2 Transformations — Tempering — Age Hardening. The most familiar transformation for strengthening steels is the martensite transformation. Carbon is far more soluble in steels at high temperature. Rapid cooling results in transformation of austenite to martensite, 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 iron carbide. This tempering of the martensite results in a reduction in strength and hardness and an increase in ductility.

Age-hardenable materials are designed to have a concentration of one or more alloying additions that exceed the solubility for that element in the alloy system. A supersaturated solid solution is accomplished by a high-temperature-solution anneal. Age hardening then occurs by precipitation of a

finely distributed second phase at a lower temperature. Heating and cooling rates with the EBW process are usually quite rapid, while solutioning and precipitation reactions are time dependent. Therefore, in some alloys it is possible to weld an age-hardened material without causing overaging (extreme precipitate coarsening leading to degradation of material properties) or in the case of solution annealed material, significant hardening due to precipitation of the aging constituent. Both solution annealing and aging temperatures are experienced in the heat-affected zone of welds.

6.2.3 Base Metal Cracking. All fusion welding processes introduce yield strength-level stress and significant plastic strain into the base metal adjacent to the weld. These are results of the thermal cycle the base metal experiences. Dimensional data taken before and after welding illustrates the amount of plastic strain taking place during EBW. If the base material is unable to accommodate these strains, it will crack. Cracking may occur just below the solidus temperature, in a low ductility trough well below the solidus temperature, at or near room temperature during subsequent heat treatment of the weldment, or both. The first two types of cracking are referred to as *hot cracking*, the third type as *cold cracking*, and the final type as *strain-age cracking*.

Hot cracking is normally intergranular. Three factors interacting with each other are identified as controlling the base-metal hot-cracking sensitivity: thermo-mechanical condition of the material, base-metal composition, and welding-process severity. Because of steep thermal gradients experienced during EBW, hot cracks tend to be limited in length in ductile materials; however, EBW is highly demanding of the base metal with regard to base metal hot-cracking tendencies when compared to the other fusion welding methods.

Cold cracking tends to be transgranular and occurs in those materials which have low room-temperature ductility such as martensitic steels. Welding the base metal in a ductile condition or preheating the material, or both, is the standard procedure for avoiding cold cracking. Good cleaning practice is important in high-strength steels to avoid hydrogen-assisted cracking.

Strain age cracking occurs primarily in alloys that are strengthened by age-hardening heat treatments and that exhibit a rapid age-hardening response. If the material is in a condition that resists stress relaxation, the residual stresses exceed the

short-time stress-rupture strength of the material and cause cracking. Strain age cracking is avoided by welding the material in an annealed or overaged condition, both of which allow for stress relaxation during subsequent heat treatment, or by using an alloy with a sluggish age-hardening response.

6.3 Fusion Zone Effects

6.3.1 Weld Structure and Cracking. As seen in Figure 8, the electron beam weld solidifies epitaxially to the base metal. Fusion zone hot cracking occurs along weld metal grain boundaries. Cold cracking occurs in the weld metal but usually is not isolated to the fusion zone. Most EBW is done autogenously, therefore, the fusion zone exhibits the same hardenability as the heat-affected zone. Filler metal is introduced when needed, as a shim in the joint, by wire feeding or other methods. This is particularly useful for alloys where changes in fusion-zone alloy composition help to avoid defects such as porosity or hot cracking.

6.3.2 Fusion Zone Porosity and Cold Shuts. Fusion zone porosity and cold shuts can be problems when electron beam welding. Porosity may occur in any electron beam welded material while cold shuts are associated with partial penetration electron beam welds. Welding on materials with high

vapor pressures in a high vacuum increases the likelihood of porosity.

As an example, welding of rimmed steel results in porosity. The porosity can be controlled by the addition of aluminum to deoxidize the steel. Aluminum is introduced as a filler wire or as a preplaced shim in the joint. Semikilled steel is less prone to porosity but still poses problems. Again, deoxidizing with aluminum reduces the porosity to an acceptable level. Slower travel speeds and beam oscillation are also useful in reducing porosity.

Many fabricators feel vacuum or double-vacuum-melted base material is an advantage for EBW-HV due to the lower gas content inherent in materials produced by these melting methods. Using beam oscillation to stir the weld pool creates a larger keyhole surface area. This helps to eliminate porosity by allowing additional time for trapped gas to migrate out of the weld. Slowing the travel speed is also effective in reducing porosity. These techniques frequently reduce or eliminate porosity and cold shut problems.

6.4 Metallurgical Considerations for Electron Beam Welding Various Materials

6.4.1 Carbon and Low Alloy Steels. Carbon steels contain up to 1.0% carbon, 1.65% manganese, and 0.60% silicon. They are used in the as-rolled, annealed, or normalized condition.

Low carbon, medium carbon and low alloy steels contain less than 0.40% carbon and are generally electron beam welded without preheat or postweld heat treatment. However, highly restrained configurations, such as deep penetration circular welds in low alloy steel, may require a 500-600°F (260-315°C) preheat to avoid cracking.

High-strength, low alloy steels contain more than 0.22% carbon. These alloys are electron beam welded in thin cross sections with moderate restraint in the annealed, normalized, or quenched and tempered conditions. The annealed or normalized conditions are favored for welding. For a highly restrained joint configuration or heavy cross section, a preheat is required. Depending on the alloy, preheat temperatures as high as 1050°F (565°C) may be required.

High carbon and tool steels contain more than 0.50% carbon. These alloys can be electron beam welded due to the limited heat input and narrow weld and heat-affected-zone width. Both preweld and postweld heat treatment are necessary to avoid cracking.

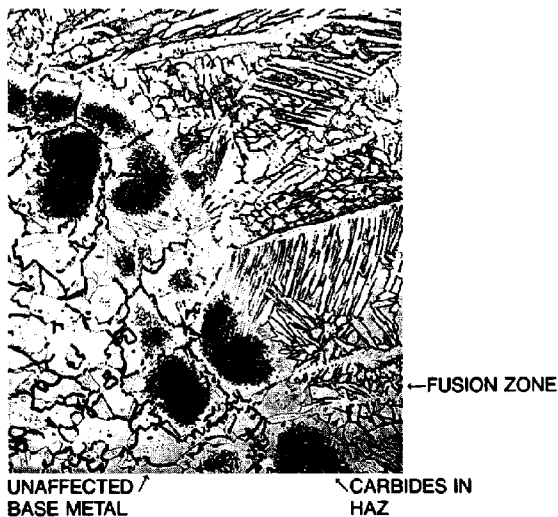


Figure 8 — Cross Section of Stainless Steel Showing the Solutioning of Carbides in the Fusion Zone

Regardless of the category of material being welded, the thermo-mechanical history of the material must be known to properly determine preweld and postweld heat treatment conditions and EBW parameters to produce the best results. By varying such things as travel speed, joint restraint, preheat, fabrication sequence, and weldment design, the level of stress and the probability of cracking are reduced.

Hydrogen-induced base metal cracking is a problem when arc welding carbon steel alloys. The high-vacuum and medium-vacuum versions of the EBW process help to avoid hydrogen embrittlement. Hydrogen containing contamination must be removed from the joint before welding.

When preheat is needed, it can be accomplished by scanning a defocused electron beam on the area to be preheated. Mass and thermal conductivity of the part govern the effectiveness of this preheating method. Lower convective heat losses in vacuum help to slow the cooling of the part, thereby, reduc-

ing cracking. Slow welding speeds add heat to the part through conduction, helping to avoid cracking.

In hardenable steels, allowing the electron beam weldment to cool in the vacuum chamber results in a slower cooling rate and helps to avoid cracking.

6.4.2 Stainless Steel. Stainless steels are those alloy steels that contain at least 10% chromium. Stainless steel alloys are classified by composition by the American Iron and Steel Institute (AISI). AISI 2XX series alloys are Cr-Ni-Mn austenitic stainless steels, AISI 3XX series alloys are Cr-Ni austenitic stainless steels, and AISI 4XX series alloys are Cr ferritic and martensitic stainless steels. There is also a series of precipitation hardened stainless steels that are identified based on their Cr and Ni contents.

The weldability of these alloys has been studied extensively from the standpoint of fusion-zone hot cracking. The Schaeffler Diagram shown in Figure 9 is used to predict phase fields in the full range of

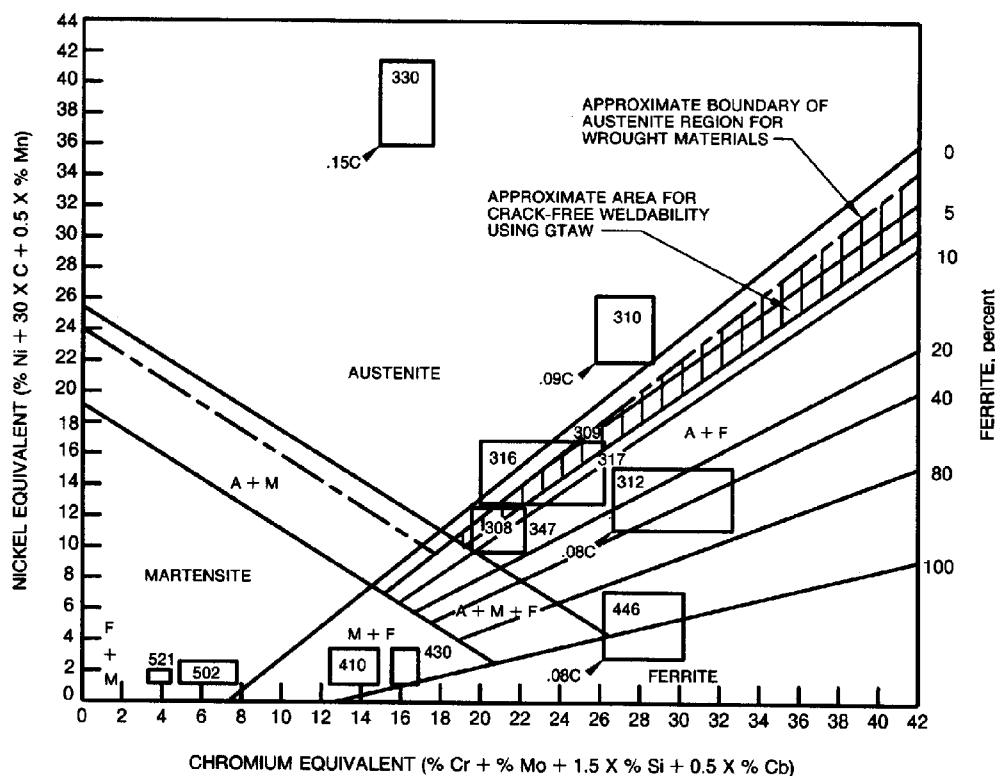


Figure 9 — Schaeffler Diagram Showing the Effects of Dilution on Dissimilar Steel Weldments

stainless steel alloys. Some alloys are shown on the diagram as well as a schematic indication of the phase fields where hot cracking and cold cracking are most prevalent. The limited width of the fusion and heat-affected zones in EBW is usually an advantage with these alloys.

Martensitic stainless steels are essentially Fe-Cr-C alloys and respond to heat treatment in a fashion similar to hardenable carbon and low alloy steels. With Cr contents between 11.5 and 18% these alloys undergo an austenite to martensite transformation during cooling after welding. The hardness of the martensite is dependent on the carbon content. As in carbon steels, the as-quenched martensitic structure has poor toughness that may be improved by tempering. These alloys can be heat treated to a softer, more ductile ferritic structure by an austenitizing treatment followed by slow cooling.

The electron beam weldability problems expected with hardenable alloys involve cold cracking due to the lack of toughness in the heat-affected and fusion zones. Preheating can be useful in avoiding cold-cracking problems. Preheat temperatures of 500-600°F (260-315°C) are normally used. The need for preheat is controlled by carbon content of the material, degree of restraint imposed by the joint design, and thickness of the joint.

Postweld heat treatment has two functions: (1) to temper the martensitic structure in the fusion and heat-affected zone, and (2) to relieve residual stresses. In autogenous electron beam welds, the fusion zone and the heat-affected zone are of similar composition which allows heat treatment to produce reasonably uniform properties across the joint. For material with greater than 0.20% carbon, it is advisable to postweld heat treat the part without allowing it to cool to room temperature. This is difficult in EBW unless expensive fixturing is used.

Ferritic stainless steels have sufficient chromium or chromium plus other ferrite stabilizers, such as aluminum, niobium, molybdenum, and titanium, to inhibit the formation of austenite at high temperature. Some austenite may form in alloys with less than 21% chromium or high interstitial contents. The austenite transforms to martensite on cooling; however, it forms in a soft ferrite matrix. The likelihood of cracking is far less than expected with martensitic stainless steel compositions. These alloys with a mixed ferrite and martensite structure may have poor ductility. Preheating may be useful for highly restrained joint configurations.

High-temperature exposure, 1700°F (925°C)

and above, causes grain growth with a resulting loss of toughness. Some of the ferritic alloys form carbides in the heat-affected-zone grain boundaries. The formation of chromium carbide results in a chromium depleted region next to the carbide with the resulting loss of corrosion resistance.

The austenitic stainless steels combine chromium with nickel, manganese, and other austenite stabilizers. Compositions that are fully austenitic in the wrought condition can have some ferrite in the cast weld metal structure. Ferrite is beneficial to the fusion-zone cracking resistance of austenitic weld metals. Weld metal ferrite can be predicted using the Schaeffler diagram shown in Figure 9. Some common alloys are shown on the diagram. In arc welding, 3 to 8% ferrite gives reasonable assurance of crack-free welds. This diagram was developed for arc welding. Thus, the higher solidification rates experienced with EBW will result in a lower-than-shown ferrite content. Unfortunately, the precise level of ferrite needed to assure a crack-free electron beam weld has not yet been defined.

The presence of ferrite, while beneficial from a cracking standpoint, is detrimental to the corrosion resistance of these alloys. Ferrite may be preferentially attacked in some corrosive environments, and transform to low-ductility sigma phase if exposed to temperatures in the 1000 to 1700°F (540 to 930°C) range for long times. Ferrite is also detrimental to the fracture toughness of these materials in cryogenic applications.

Austenitic stainless steels, when heated into the 800 to 1600°F (420 to 870°C) temperature range, precipitate carbides primarily along the grain boundaries. This precipitation, called *sensitization*, leaves a chromium depleted region which causes reduced corrosion resistance in some media. Niobium and titanium are used as stabilizers in some grades to overcome this problem. The narrow heat-affected zone in EBW minimizes sensitization, but the potential for its occurrence is still present.

Austenitic stainless steels exhibit stress corrosion cracking under some conditions. Residual tensile stresses combined with the appropriate corrosive environment results in either transgranular or intergranular cracking. The ions in the halogen family (chlorine, fluorine, bromine, and iodine) cause the greatest number of failures. Electron beam welds typically have smaller residual stresses than other welds, but they are not stress-free and are subject to stress corrosion cracking. Stress relief

improves the problem, although the heat treatment must be designed to avoid sensitization.

Precipitation-hardened stainless steels achieve high-strength levels by a precipitation-hardening thermal treatment or a combination of precipitation hardening and martensitic transformation. Precipitation hardening is developed by alloying with elements such as copper, titanium, aluminum, and niobium. Strength is achieved by precipitation of submicroscopic particles in the microstructure. These high-strength levels are achieved while retaining a reasonable level of ductility and fracture toughness. Precipitation-hardened alloys are grouped into three categories: austenitic, semiaustenitic, and martensitic.

Welding is usually done in the solution annealed or overaged condition. To achieve the full properties of the alloy it is necessary to heat treat after welding. If precipitation-hardened alloys are welded in the hardened condition a narrow region is created in the heat-affected zone where the precipitate is redissolved which causes softening. Again heat treatment is required to achieve full strength over the entire cross section.

Austenitic, precipitation-hardened materials are subject to heat-affected-zone cracking and are difficult to weld. Other precipitation-hardened stainless steels do not pose any special problems.

6.4.3 Nickel- and Cobalt-Based Alloys. Nickel is used as an industrial material in a relatively pure form and alloyed with substantial amounts of copper, chromium, iron, molybdenum, aluminum, titanium, niobium, and tungsten. Most nickel-base alloys are weldable by EBW.

Pure nickel has relatively high thermal conductivity and poor fluidity. The absence of residual deoxidizers in the composition can lead to porosity problems. Beam oscillation is used to hold the molten pool open longer and reduce porosity. This technique is universally applied to nickel-base alloys, unless the material is contaminated with sulphur or other materials which form low melting eutectics.

Nickel-copper alloys have characteristics similar to nickel. The copper-nickel alloys tend to be more characteristic of copper. While porosity is a problem with these alloys; cracking is not generally a problem.

Iron-nickel-chromium, nickel-chromium-iron, nickel-molybdenum, nickel-chromium, nickel-chromium-molybdenum-cobalt, and nickel-chromium-molybdenum alloys have fusion-zone

cracking problems. As with the austenitic stainless steels, phosphorous, sulphur and other residual elements need to be maintained at a low level to ensure welds free of fusion-zone cracking.

Heat-affected-zone cracking is a problem in materials with coarse grain sizes. Grain-coarsening treatments are frequently used to develop optimum high-temperature creep and stress-rupture properties. Heat-affected-zone cracking resistance is also affected by boron and zirconium levels.

Nickel-base alloys are age hardened by the addition of aluminum, titanium, niobium, and combinations of these elements. The aluminum, and aluminum plus titanium, hardened alloys have a rapid aging response and are consequently subject to strain age cracking. The niobium age-hardened alloys have a sluggish aging response and are not prone to strain age cracking. Age-hardenable compositions are also subject to the same fusion-zone and heat-affected-zone cracking problems as other nickel-base alloys.

Cobalt is not typically used in an unalloyed form. Cobalt alloys contain tungsten, chromium, nickel, or molybdenum, or a combination of these, as solution strengtheners. Small additions of niobium, titanium, vanadium, boron, and zirconium are used to improve high temperature properties. Within proper limits, none of these elements adversely affect the weldability of cobalt-base alloys, although excessive amounts can cause fusion-zone and heat-affected-zone cracking problems. Carbon, silicon, iron, and manganese are also present in these alloys. Excessive amounts of carbon and silicon degrade the weldability if present in excessive amounts.

6.4.4 Copper and Copper-Base Alloys. Copper is useful in its unalloyed form primarily for its thermal and electrical conductivity. The high thermal conductivity of these alloys is a problem for most fusion welding processes; however, it affects EBW only minimally.

In its unalloyed form, copper is used in oxygen-free and oxygen-bearing grades. Electron beam welding of oxygen-bearing copper results in porosity and spatter due to the evolution of residual oxygen. Welding on oxygen-free or deoxidized grades produces better weld quality.

Major alloying elements added to copper are zinc (brasses), tin (phosphor bronzes), aluminum (aluminum bronze), silicon (silicon bronzes), and nickel (copper-nickel). Zinc alloying poses problems because of its high vapor pressure which

allows it to evaporate from the fusion zone during welding. Electron beam welding of brass results in porosity and significant composition change in the alloy, along with zinc plating on the walls of the vacuum equipment. Cadmium and phosphorous bearing alloys pose similar problems.

Copper is age hardened with the addition of beryllium, chromium, and zirconium. The same general rules apply for welding age-hardening copper alloys as with other age-hardenable materials.

6.4.5 Aluminum and Aluminum Alloys. Aluminum is used in its pure form or alloyed with copper, magnesium, manganese, silicon or zinc. Small additions of chromium, iron, nickel, and titanium are also made to improve physical properties. Magnesium, manganese, silicon, and iron individually or in a combination are solid-solution strengtheners. The addition of copper, magnesium, silicon, and zinc produce alloys which can be heat treated to achieve high-strength properties.

Aluminum forms a tenacious surface oxide on exposure to air. Removal of this oxide just prior to welding is important to controlling the porosity level of electron beam welds. Oxide removal by scraping, machining, or pickling is preferred for EBW since no residual particles are left on, or embedded in, the surface to interact with the electron beam causing spatter and porosity.

Pure aluminum (1100), and some of the alloys in the 2XXX, 3XXX, 4XXX, and 5XXX series are electron beam welded autogenously without fusion-zone or heat-affected-zone cracking problems. Other aluminum alloys require filler metal to overcome fusion-zone cracking problems. The narrow heat-affected zones of electron beam welds limit the amount of eutectic melting in the partially melted zone. This is beneficial in limiting the amount of heat-affected-zone cracking. This is further improved by using high welding speeds and minimum heat input.

Significant quantities of high-vapor-pressure alloying elements such as magnesium in the 5XXX series aluminum alloys, are preferentially vaporized. Because of this, mechanical properties of the resulting lower alloy-content fusion zone can be significantly different than the base-metal properties. Zinc is the principal alloying element in the 7XXX series alloys. As in other systems, the high vapor pressure of zinc causes porosity problems.

6.4.6 Magnesium and Magnesium Alloys. Due to the high vapor pressure of magnesium, EBW is

limited. Zinc, the principal alloying element in magnesium alloys, has an even higher vapor pressure than magnesium. Alloys with more than 1% zinc are usually not electron beam welded. Beam oscillation or use of a slightly defocused beam can be helpful in controlling porosity.

6.4.7 Titanium and Titanium Alloys. Titanium is used in its pure form as well as being alloyed with a number of different elements. Pure titanium undergoes an allotropic transformation from hexagonal, close-packed alpha phase to body-centered cubic beta phase at about 1625°F (885°C). Titanium alloys are classed as alpha, alpha plus beta, and beta alloys. Titanium alloys are extremely reactive and must be thoroughly protected when welded. EBW operated in high or medium vacuum, provides an excellent welding atmosphere. Vacuum eliminates problems with nitrogen, oxygen, and hydrogen contamination.

Pure titanium and alloys with aluminum and tin are alpha-phase alloys. The alpha alloys have good strength, toughness, and weldability.

Beta-phase alloys contain varying amounts of vanadium, niobium, tantalum, and molybdenum. These alloys have good formability and weldability in the annealed and solution heat-treated conditions.

Dual-phase (alpha plus beta) alloys contain a mixture of the two phases at room temperature. The Ti-6Al-4V alloy is the best known alloy of this group. These alloys contain from 10 to 50% beta phase at room temperature. If there is more than about 20% beta phase present the alloys are not weldable. The amount of beta phase present is controlled to some extent by heat treatment.

6.4.8 Refractory Metals and Alloys (Tungsten, Molybdenum, Tantalum, and Niobium). All refractory materials are sensitive to contamination by the interstitial elements — carbon, nitrogen, oxygen, and hydrogen — which reduce ductility and increase notch sensitivity. These materials, especially the pure metals, exhibit extensive grain growth in the weld heat-affected zone. Coarse grain-size materials exhibit reduced ductility that leads to cracking during welding or in fabrication. The EBW-HV and EBW-MV processes generally produce a narrow heat-affected zone and are the preferred welding methods for refractory metals and alloys.

Tungsten is the most difficult of the refractory metals to weld due to its near zero ductility at room temperature and high melting temperature. Tung-

sten undergoes a ductile-to-brittle transition above room temperature. Thin sheet metal can be welded without preheat if the restraint on the joint is minimized. Preheat will be necessary for most weldments and should be above the ductile-to-brittle transition at 575°F (300°C). Tungsten alloys, especially with rhenium, exhibit much better weldability and mechanical properties. The improvement is due to increased ductility at room temperature.

Molybdenum in a fine grain condition has a ductile-to-brittle transition temperature below room temperature. Fusion welding results in grain growth in the heat-affected zone and a coarse-grained weld-fusion-zone structure which results in a transition temperature above room temperature. Again as with tungsten, minimizing joint restraint is necessary to avoid cracking. Preheating to at least 400°F (205°C) followed by a stress relief heat treatment of 1600-1800°F (870-980°C) is beneficial. This heat treatment, however, will not restore the room temperature ductility.

Molybdenum is alloyed with small amounts of titanium, zirconium, and carbon to improve its high temperature strength. The alloying results in slight improvements in the as-welded material properties. The increase is attributed to finer grain size in the alloy. Molybdenum, like tungsten, is also alloyed with rhenium. The rhenium substantially improves the room temperature ductility and weldability.

Unalloyed niobium and tantalum are much more readily welded than either tungsten or molybdenum since both undergo a low-temperature ductile-to-brittle transition. Both have excellent room temperature ductility and, although they experience grain growth in the heat-affected zone, adequate ductility remains to avoid cracking. Niobium and tantalum alloys also exhibit good electron beam weldability. Grain growth in the heat-affected zone and fusion zone is limited in the alloys as compared to the pure metals.

6.5 Metallurgical Considerations for Welding Dissimilar Metals. One of the more interesting materials considerations appearing in recent years is that of welding dissimilar metals. This has come about due to the need for specific materials properties in one region of a part while different properties are needed elsewhere on the same part.

For example, in the nuclear industry, 304-to-316 stainless steel or 5083-to-1100 aluminum are common dissimilar metal joints. Another example is the joining of the hardened cutting blade of a band-

saw to the less expensive and more ductile body material.

Joining of dissimilar metals leads to special problems in both solidification and processing. In the area of solidification, attention must be paid to the chemistry of both metals as well as to the resulting fusion zone. Without this attention, cracking is likely to occur. In stainless steels, cracking usually results from too little ferrite in the fusion zone. Low alloy or hardenable steels usually crack as a result of the formation of martensite, although they too can crack as a result of low ferrite. Joining of dissimilar aluminum alloys can result in joints with cracks as a result of insufficient alloy content (References 1, 2, 3, and 4).

Differences in thermal expansion also create problems when welding dissimilar steels. Here again, the problem is usually cracking as a result of residual stress and chemistry of the parent metals. Often the difficulty can be avoided or eliminated by proper joint design. As an example, cracking between beryllium alloys with different oxide contents can be eliminated or reduced by using a standing edge joint. Frequently, an interference fit can be used to form the joint and reduce the effect of thermal mismatch. The interference fit must be designed so that compression of the joint occurs on cooling.

Often the resulting weld profile is seen to bend toward one material in dissimilar metal joints. This has been shown to be a result of the thermoelectric effect (Reference 5). As explained by Blakely, the effect is a result of the weld pool forming a hot junction between different alloys, while a cold junction is formed by the metal outside the heat-affected zone. The thermoelectric currents flowing as a result of the temperature gradient between the junctions create a magnetic field which deflects the beam away from the joint. It is shown that fields of approximately 10 gauss result if the thermoelectric potential difference is several millivolts and the resistivity of the materials is on the order of tens of micro-ohms.

High-strength materials, dissimilar metal joints, and joining of crack-sensitive materials has led to the use of filler metal wire feed with EBW. A normal electron beam wire-feed weld can be expected to require at least two passes and frequently many more. The first pass is usually an autogenous pass, but, if chemistry control is important it can also utilize filler wire addition. At the end of one pass the voltage, current, focus, part speed and wire position can be changed (the wire position must be changed to compensate for the metal added).

In greatly dissimilar materials, such as stainless steel to aluminum or nickel to copper, the use of equilibrium phase diagrams may be helpful in deciding whether a weld can be made. Experience has shown that many materials that would usually crack or exhibit other problems when welded may, under the proper process control, make satisfactory welds. Greatly dissimilar melting points may allow one material to be wet onto another forming a braze weld which is sufficient for many applications. In other cases, the solubility limits are such that slight alloying in the fusion zone is acceptable, while larger amounts cause weldability problems. In general, a small number of test welds give much needed information on the dissimilar material combination.

6.6 References

- (1) Dowd, J. D. "Weld cracking of aluminum alloys.", *Welding Journal*, Research Supplement 31 (10): 448 - 456, 1952.
- (2) Jennings, P.H., Singer, A. R. E., and Pumphrey, W. I. "Hot shortness of some high-purity alloys in the systems aluminum-copper-silicon and aluminum-magnesium-silicon." *Journal of the Institute of Metals* (74): 227 - 248, 1948.
- (3) Singer, A. R. E., and Jennings, P. H. "Hot-shortness of the aluminum-silicon alloys of commercial purity." *Journal of the Institute of Metals* (73): 197 - 212, 1947.
- (4) Pumphrey, W. I. and Lyons, J. V. "Cracking during the casting and welding of the more common binary aluminum alloys." *Journal of the Institute of Metals* (74): 439 - 455, 1948.
- (5) Blakely, P. J. and Sanderson, A. "The origin and effects of manetic fields in electron beam welding," *Welding Journal* 63(1): 42 - 49, 1984.

7. General Process Considerations

7.1 Overview. Due to the high power density achieved in a focused electron beam, the welding process is not limited or controlled by thermal conduction. This enables metals with high thermal conductivity, or joint designs with asymmetric heat transfer characteristics, to be successfully joined. The high weld-aspect-ratio characteristic permits joint designs that do not require the addition of filler metal.

Precision welding fixtures are required to maintain joint alignment. Workpieces and fixtures should be demagnetized regularly to avoid deflection and, therefore, misalignment of the electron beam. Required joint fit-up tolerances depend on

the process mode employed, base metal, joint thickness, and the desired weld quality.

Contamination can cause defects and deterioration of weld metal properties. While cleanliness is important to produce quality welds, specific cleanliness requirements depend on the weld application. Beam oscillation or defocusing, or both, can be utilized to reduce porosity, produce wider welds, retard cooling rates, or modify weld-bead shape.

7.1.1. Electron Beam Welding in Vacuum. EBW in a vacuum (EBW-HV and EBW-MV) normally requires the workpiece and the tooling to be completely contained in a vacuum chamber. Vacuum processing provides the purest atmosphere and is used to produce hermetic closures that retain vacuum. Workpiece materials that outgas are not acceptable with these vacuum modes, as they contaminate the atmosphere. Provisions must be made to vent regions of the workpiece which trap gas or volatile materials. Improper cleaning of the workpiece or tooling increases evacuation time, degrades vacuum-pump oil and has detrimental effects on high voltage operation.

7.1.1.1 High-Vacuum Electron Beam Welding. EBW-HV produces high-quality, high-aspect-ratio welds with a minimum of contamination. Beam divergence is minimal and working distances of several feet are possible. EBW-HV requires significant evacuation times. This limits its use to batch work with low production rates and high cost, although proper tooling reduces the cost per part. This mode is ideally suited for welding reactive and refractory metals.

The smallest focal spot sizes are attained in EBW-HV. The small focal spot size mandates special precautions be taken in joint design and fit-up. A high standard of machining is required to ensure close abutment to avoid underfill or incomplete fusion.

7.1.1.2 Medium-Vacuum Electron Beam Welding. EBW-MV results in higher production rates than EBW-HV due to the relatively rapid evacuation time. Increased gas pressure within the welding chamber produces welds with higher gas content that may result in increased porosity. Larger beam divergence, caused by more electron/air molecule interactions results in wider weld geometries.

7.1.2 Nonvacuum Electron Beam Welding. EBW-NV has the highest production rates and low-

est costs per part of the EBW processes since there is no evacuation time involved. The welding atmosphere scatters the beam which results in decreased power density, lower aspect ratio welds compared to those of equivalent power made in vacuum. Workpiece size is not limited by a welding chamber but rather by the radiation shielding. Product design (shape) is limited by the short working distance. Odd shapes, protrusions, or depressions are not suitable for this mode.

7.2 Designing for Electron Beam Welding

7.2.1 Joint and Weld Types. EBW is used with butt, T-, corner, lap, and edge joints. Common

weld types include square-groove, seam, edge, flange, and fillet. Since EBW usually does not use or need a filler wire, neither V-grooves nor corners can be filled; in fact, they are detrimental. Fillet welds are readily made with EBW-NV and are made with vacuum EBW modes by reducing the energy density by defocusing or by beam oscillation, or both. Fillet welds find less usage with vacuum EBW because square-groove welds can be applied to the same joints to produce equivalent weld sizes with substantially lower heat input.

7.2.1.1 Welds in Butt Joints. Figure 10(A) illustrates the basic square-groove weld applied to a butt joint. Penetration may be partial or complete

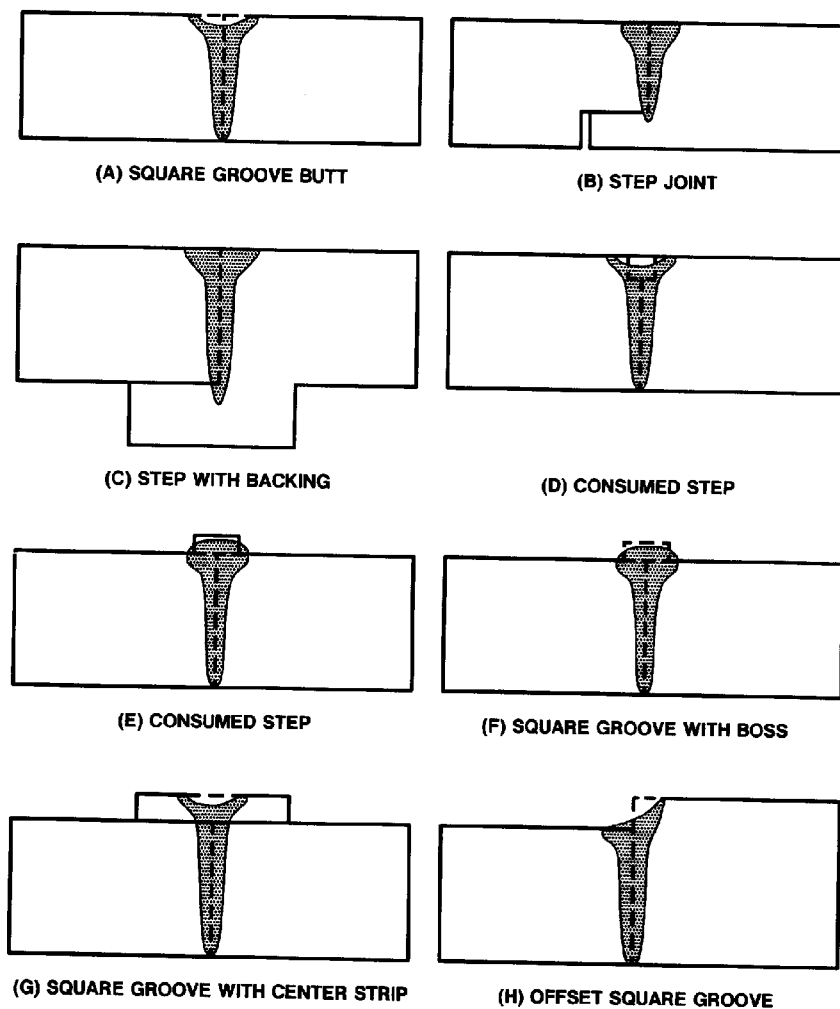


Figure 10 — Various Joints Used in EBW

and welding may be from one or both sides. Joint preparation is simple; however, the joint requires good fit-up and external fixtures for alignment.

A step may be added to the joint to facilitate part alignment. Figure 10(B) illustrates an integral step for joint alignment. The clearance gap shown in the step is an allowance for shrinkage to reduce joint restraint. The butt joint in Figure 10(C) utilizes a backing bar to establish alignment. This backing may be integral or separate. Figures 10(D) and 10(E) illustrate self-aligning joints which use a step that is completely consumed by the weld. The step may be on either the face or the root side of the weld. Placing the step on the face side permits a larger step by positioning it in the widest part of the weld; however, the principal faying surfaces of the joint are concealed and some means must be provided to establish proper beam-to-joint alignment. One such method involves the use of witness lines. The self-aligning methods discussed above may also be self-fixturing in circular, circumferential, and certain other part configurations.

The designer must keep in mind that while integral steps are a substantial aid to maintaining alignment of the parts, machining costs are higher. Not as obvious is that weld quality (soundness) may suffer. The internal corners are more prone to entrap foreign material and are difficult to clean. Welds in some metals, such as titanium, are especially liable to contain porosity as a direct result of joint surface contamination.

The joint backing illustrated in Figures 10(B) and 10(C) limits underfill and prevents melt-through and weld spatter on the root side of complete joint penetration welds. Root defects resulting from spiking can be contained within the backing which may be removed.

Underfill in complete joint penetration welds is controlled by the incorporation of auxiliary filler metal. The design shown in Figure 10(E) assists in joint alignment but conceals the principal faying surfaces from beam alignment. The design of Figure 10(F) provides filler and permits direct viewing of the joint, but requires other provisions for joint alignment. The joint shown in Figure 10(G) uses a cover strip as a feature to control underfill. The cover strip may be integral or separate and is removed after welding. The cover strip can assist joint alignment but this conceals the actual weld joint. The shoulder illustrated in Figure 10(H) is used to control underfill but care must be taken because a small lateral shift of the beam from the low to high side, and vice versa, changes the joint pene-

tration. Flush joints are preferred because control of conditions for making sound, complete joint penetration welds are less critical.

7.2.1.2 Welds in T-joints. Figures 11(A) and 11(B) illustrate the basic square-groove weld applied to T-joints. Features common to the basic square-groove welded butt joint apply to square-groove welded T-joints as well. Figure 7.2c illustrates the application of a seam weld to a T-joint. Seam

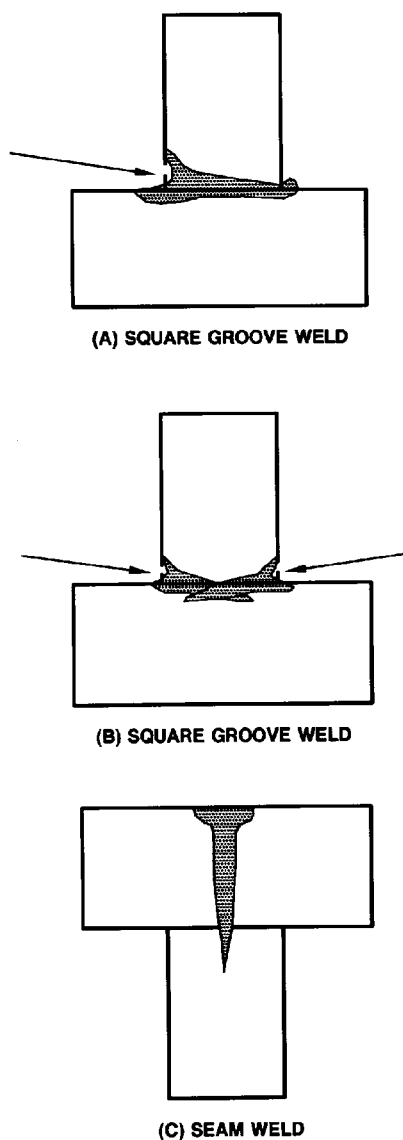


Figure 11 — T-Joint Configurations

welded joints must be carefully considered before use as these designs are not as structurally sound as square-groove welded joints and present difficult inspection conditions. A reduction of the joint strength, due to a smaller surface area of joined material, and fatigue properties, due to the notches that remain after welding, are typical of this design.

7.2.1.3 Welds in Corner Joints. Figure 12 illustrates typical welds in corner joints. Features common to square-groove and seam welded joints discussed in the sections on butt and T-joints apply to corner joints joined with similar welds. The corner-flange joint is used on welds on thin materials with precision formed edges. This requires precision tooling to ensure a tight joint fit-up. Power density is generally reduced to produce conduction mode melting when making corner-flange welds.

7.2.1.4 Welds in Lap Joints. Figure 13 illustrates typical welds in lap joints. Features common to the basic square-groove welded butt joint apply to lap joints with similar welds. Similar seam welded lap and T-joints have comparable mechanical properties. Fillet welds can be made on lap joints in thin materials with reduced beam power density.

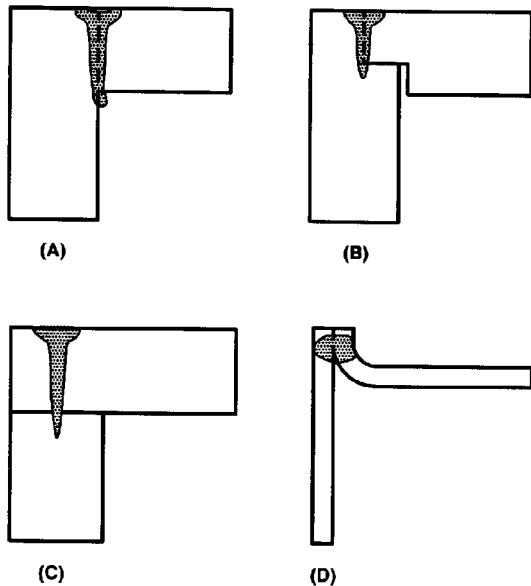


Figure 12 — Various Corner Joint Configurations

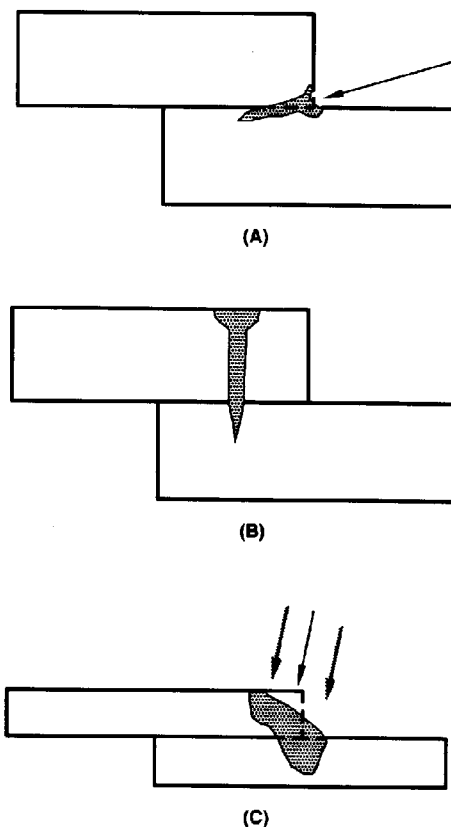


Figure 13 — Various Lap Joint Configurations

7.2.1.5 Welds in Edge Joints. Figure 14 illustrates welds used to fuse edge joints. Square-groove welds are used on edge joints in thick sections. Mechanical properties are similar to the basic square-groove welded butt joint with partial penetration. Edge weld joints made between thin and dissimilar thickness materials have mechanical properties similar to those of corner-flange welds.

7.2.2 Design Considerations

7.2.2.1 Joint Accessibility. A distinct feature of electron beam welding in a vacuum is that welds can be made in relatively inaccessible places. The joint can be welded if positioned within the optical line of sight of the beam. The beam can be projected over a substantial distance through narrow openings to weld in areas of limited access. This characteristic of vacuum electron beam welding

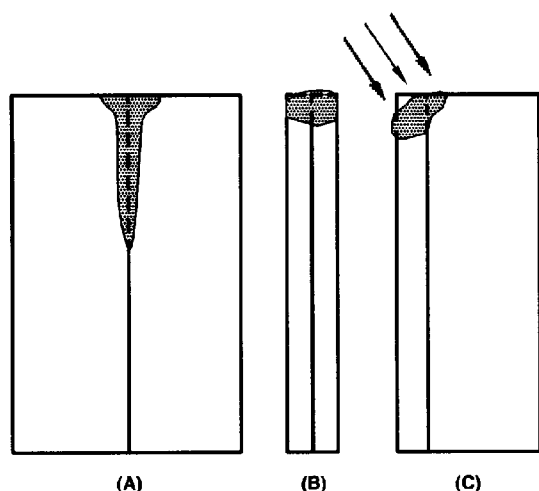


Figure 14 — Various Edge Joint Configurations

allows some unique design opportunities. Accessibility is limited in EBW-NV due to the short gun-to-work distances available.

7.2.2.2 Joint Details. Electron beam welding generally requires precision joints. The degree of precision or sophistication demanded depends on a number of factors which include: machine operating parameters, part size and geometry, type of joint geometry, thickness and type of material being welded, and weld quality acceptance criteria. Nonetheless, gaps or voids within a joint to be electron beam welded are considered detrimental. A zero gap is best, but not usually attainable. With the objective of minimal gap in mind, attention must be given to the joint details with regard to all dimensions including squareness, flatness, radii, chamfers, tolerances, and surface finish. More detailed information on acceptable gaps is found in sections 7.4 and 7.5.

Consideration should be given to the use of self-aligning and self-fixturing joint designs to facilitate control of joint alignment and reduce assembly time. When large numbers of parts are being fabricated, close tolerance fixtures are usually more cost effective.

In some instances, a provision must be made for venting before welding a closed volume. Venting is accomplished with small grooves on the faying sur-

faces, or occasionally, by leaving a vent hole which is subsequently sealed.

7.2.2.3 Shrinkage. While minimum heat input and low thermal distortion are important advantages of electron beam welding, the molten metal still shrinks as it solidifies. If the joint volume is completely restrained and the part is unable to shrink at a corresponding rate the material is left in a stressed condition. Such joints are practical in easily welded metals (ductile with low yield strengths and small shrinkage) but not in difficult-to-weld materials which have high strength or hardness properties. Failure to make allowance for weld shrinkage can result in cracking during or after welding, during subsequent heat treatment, or while in service.

Circular welds, for example, experience severe restraint, as in Figure 15(A). As an alternate, the joint configuration may be changed to utilize a circumferential (radial) weld which has minimal shrinkage stress, as in Figure 15(B). The volume of molten metal is not constrained in the axial direction if the hub is allowed to move, the joint has root clearance, and the weld zone does not extend into the shaft. Where circular welds must be used, joint restraint is reduced by the use of relief grooves adjacent to the weld. Shrink or press-fit joints are also helpful in reducing residual stresses in circular welds.

Joint restraint imposed by self-aligning steps should be avoided by designing shrinkage gaps into

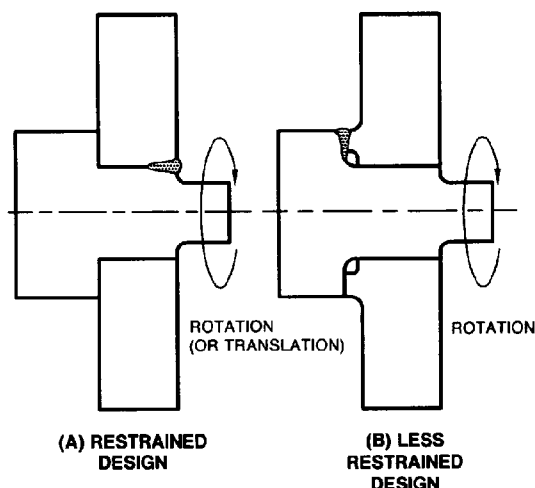


Figure 15 — Circular Joints

these joints. If necessary, allow excess material for the shrinkage and machining after welding. Caution must be used in specifying joints to be welded from both sides as the second pass is exposed to substantial restraint.

7.2.2.4 Structural Considerations. Corner joints and seam welded T-joints have inherently high-stress concentrations. This concentration of stress at a weld in a corner or T-joint is avoided by designing for a butt joint on a straight section near the corner or T. This principle of design is applicable to butt joints between members having different thicknesses, and is applied to straight line, circular, and circumferential joints.

Although self-backing joints have several benefits (ease of joint alignment, control of underfill, absence of spatter at weld root, no melt-through) these joints also have some disadvantages related to the unwelded joint near the weld root. There is a stress concentration associated with the unwelded joint and its severity depends on the specific joint configuration, loading, and service conditions (which might include corrosion considerations and consequences of failure).

Partial joint penetration welds are subject to root discontinuities due to a condition known as *spiking*. Partial joint penetration welds include those welded from both sides and downslope sections of welds. Electron beam weld penetration fluctuates rapidly, particularly when operating at higher-power densities. This causes voids or cold shuts at the weld root which may be difficult to detect. One solution to avoid spiking discontinuities is to weld into a backing bar which is later removed. Other solutions include developing parameters that minimize spiking by using slight defocus or beam oscillation. Defects may be reduced at the end of the weld by downsloping the welding parameters.

Inspectability of electron beam welds varies widely depending upon the specific joint design, weldment configuration, and inspection method. At one extreme, the choice of joint and weld design is influenced only minimally by the ability to inspect the completed joint. At the other extreme, the selection of joint design is dictated solely by the ability to perform specific nondestructive examinations.

7.2.2.5 Drawing Requirements. Drawings should specify the proper joint design by controlling the dimensions of all joint details which affect configuration and fit. Squareness, flatness, radii, chamfers, tolerances, and surface finish of the de-

tails should be specified congruent with the fit-up (gap and mismatch) required in the finished assembly. The assembly drawing should include the proper welding symbol and information. The required inspections can be denoted by using the appropriate symbols from ANSI/AWS A2.4 *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, or drawing notes. Process controls should be specified on the engineering drawing, in the form of drawing notes, or by reference to a welding procedure which controls cleaning procedures, welding operator certification requirements, and the welding process.

7.3 Joint Cleaning. Joint cleanliness is of the utmost importance in EBW. The effects of joint contamination include weld spatter, excessive cratering, and porosity. Since the volume of metal melted is less with EBW, contamination that would be diluted and not affect a GTA weld can seriously affect an electron beam weld. Residue on joints or parts may be composed of materials with largely different vapor pressures that can preferentially evaporate in the electron beam welder-vacuum environment. This leads to contamination of equipment as well as the weld joint. These residues also affect the chamber pumping speed in EBW-HV. It is best to ensure that the joint is clean prior to welding.

A common pitfall in part cleaning is improper handling after cleaning and before welding. It is recommended that lint-free gloves be used instead of rubber gloves and that parts be stored in clean areas. To further ensure optimum cleanliness, it is recommended that preweld cleaning and final assembly be done just prior to welding at the EBW facility. Part protection materials should be compatible with the parts, as an example, many metals contaminate refractory metal weld joints.

Table 2 lists many materials and cleaning methods common for electron beam welded parts. Improved cleaning agents are continually developed. Chemical manufacturers should be consulted as to residues or safety considerations before a particular agent is chosen. These materials and steps are intended as guidelines and should not be used in place of established procedures for preweld cleaning.

7.4 Welding Thin Metals. The electron beam process has the advantage of being able to be focused to a beam spot as small as 0.005 in. (0.127 mm) diameter. This is particularly useful for welding

Table 2
Preweld Cleaning Materials^a

Degrease		Chemical Clean	Electro Polish	Mechanical
(1) Acetone	(1) 10% Caustic Soda	(1) 10% Caustic Soda	(1) Stainless Wire Brush	
(2) TCFE	(2) 20-50% HNO ₃	(2) 25-70% H ₂ SO ₄	(2) Emery	
(3) M.E.K.	(3) HNO ₃ -HF		(3) Scrape	
(4) Alcohol			(4) Machine	
Alloys	Degrease	Chemical Clean	Electro Polish	Mechanical
Aluminum	1 or 2	1 and 2		1 and 4
Mild steel	1 or 2		2	1 and 4
Beryllium	1 or 2			4
Stainless	1 or 2		2	4
High nickel	1 or 2		2	4
Cobalt	1 or 2		2	4
Copper	1 or 2	2		4
Titanium	2 or 3 ^b	3		4
Uranium	1	2	2	4
Precious				
Gold	1, 2, 3 or 4			4
Platinum	1, 2, 3 or 4			4
Palladium	1, 2, 3 or 4			4
Silver	1, 2, 3 or 4			4
Heavy metals	1, 2, 3 or 4			4
Refractories				
Niobium	1, 2, 3 or 4	3		4
Tungsten	1, 2, 3 or 4	1 and 3	1	4
Molybdenum	1, 2, 3 or 4		2	4
Zirconium	1, 2, 3 or 4	3		4
Tantalum	1, 2, 3 or 4	3		4
Vanadium	1, 2, 3 or 4	3		4
Rhenium	1, 2, 3 or 4	2		4

Notes:

- This table is intended as a guideline and includes typical preweld cleaning operations. These procedures should not be substituted for established procedures that specify preweld cleaning.
- Do not degrease titanium with chlorinated hydrocarbons or alcohol. Acid etching produces more even cleaning than electropolishing. Experience shows that the use of trichloroethylene as a solvent on parts or machine components causes problems during corona clear.

thin-section materials. As with all welding processes useful for thin-section welding, the standing-edge weld-joint configuration is the best joint design with a lap joint being second choice. The least desirable configuration is a butt joint.

Fixturing and tooling control the success of thin cross section welding. Fixturing and tooling serve three functions:

(1) To ensure precise positioning of the joint to be welded

(2) To prevent movement of the part due to thermal strain

(3) To act as a heatsink to control heat flow

Copper and aluminum are the most frequently used materials for fixturing. Both materials have excellent thermal conductivity and are not ferromagnetic. Where copper pick-up in the weld zone may result in hotcracking, i.e., steels or nickel, plating of copper fixtures is advised.

As a general rule, the joint fit-up should be such

as to avoid gaps that exceed 5-10% (depending on finished weld requirements) of the thinnest section being welded. This guideline is reasonably easy to implement for thicknesses of 0.010 in. (0.255 mm) and greater. For thicknesses below 0.010 in. (0.25 mm), and particularly below 0.005 in. (0.13 mm), gauging the joint fit-up becomes increasingly more difficult. Surface finishes and flatness on tooling become critical with thin materials in order to meet part specifications.

7.5 Welding Thick Metals. Thick sections are defined as the approximate thickness at which the force of gravity acting on the liquid metal in the keyhole overcomes surface tension forces when welding in the flat position. Consequently, EBW of thick sections is usually performed horizontally.

The high specific energy of the electron beam, together with the associated precise control of welding variables and reproducibility of developed procedures, offer significant economic benefits for thick-section welding. These characteristics result in the following advantages:

(1) Deep penetration, producing a parallel-sided weld in a single pass. The ability of a 200 kW electron beam system to weld 12 in. (300 mm) thick plate of 2-1/4 Cr-Mo steel in one pass has been demonstrated (Reference 1).

(2) Very high productivity in comparison with conventional arc welding. A study of joint-completion rate expressed in hours per foot of completed weld seam in 8 in. (200 mm) thick plate (Reference 2) gave the following values:

(a) Manual Arc Welding	40 h/ft (130h/m)
(b) Submerged arc welding (Tandem arc)	3.0 h/ft (10h/m)
(c) Electron beam	0.067 h/ft (0.22h/m)

(3) No filler material is required.

(4) Structural steels and pressure vessel steels are electron beam welded without preheating. A postweld stress relief heat treatment is generally beneficial to the material properties.

(5) Hydrogen cracking is reduced by using a vacuum welding environment.

The technique for welding heavy plate requires development of welding parameters that ensure a stable cavity is maintained over the entire joint length. The first requirement is "overpower"; that is, a welding power level 20-50% greater than the power required to just penetrate the thickness to be welded (Reference 2). Overpowering, the proper location of the focal spot, and beam oscillation

combine to provide keyhole stability. Fortunately, the selection of welding parameters that provide an essentially straight-sided weld geometry promotes cavity stability when the overpowering is adequate. The required weld geometry is achieved by setting the focal spot well below the surface of the work.

There is some leeway in the selection of welding speed, so that the rate of energy input can be adjusted (within limits) to accommodate the metallurgical characteristics of the material being welded. The combination of focal spot position, welding speed, and beam oscillation affect the solidification structure of the liquid metal. Solidification front lag must be minimized by the selection of the welding parameters. Relatively low welding speed reduces lag in the solidification front. Nevertheless, in thick section welding the cooling rate is quite high, and may either enhance or detract from the desired metallurgical properties.

Square-groove butt joints are preferred for thick-section EBW. The fit-up must be controlled such that the maximum joint opening is on the order of 1% of the material thickness. The weld must be wide enough to span both faces of the butt joint. Excessive gapping results in underfill. This is undesirable but is corrected by an additional welding pass utilizing filler wire.

Thick-section welding requires that the weld be produced in a vacuum of 2×10^{-2} torr (2.7 pascal) or lower. Very large vacuum chambers (Figure 16) are manufactured for welding large, thick structures. However, portable, local vacuum apparatus that conform to the surface of the part to be welded are used successfully (Reference 2, 3).

Residual magnetism in thick-section steel components being electron beam welded presents a severe problem. The leakage flux from residual magnetism deflects the electron beam, moving it away from the joint, causing an incomplete fusion defect. Two effective methods in preventing beam deflection are demagnetization of parts and shielding of the electron beam (Reference 4).

Since electron beam welding of thick sections is principally an autogenous welding process, the composition and microstructure of the weld metal and heat-affected zone are determined essentially by the composition of the workpiece. The welding parameters are selected principally to provide an essentially straight-sided weld geometry and a satisfactory reinforcement and underbead. The "as welded" metallurgical properties of thick section electron beam welds are determined largely by cooling rate.

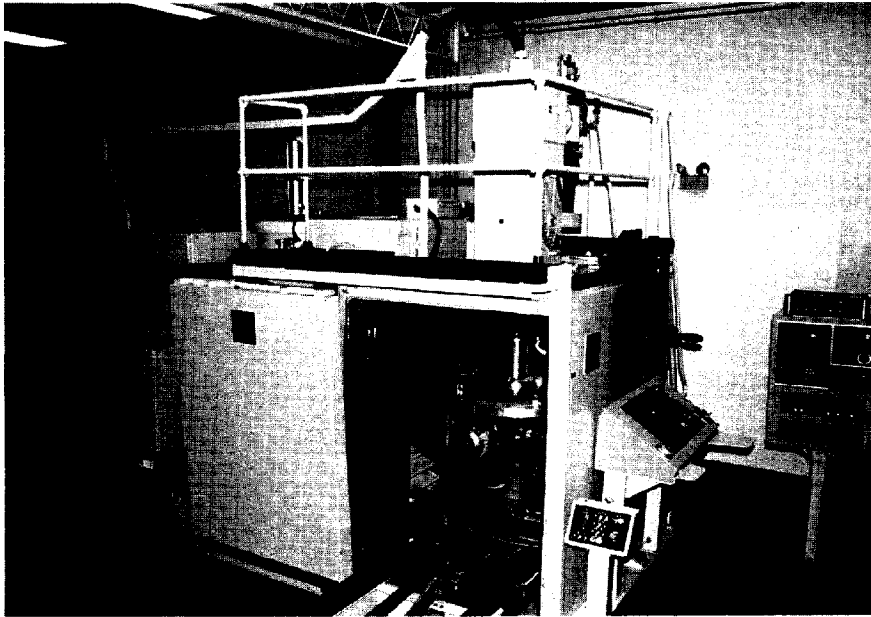


Figure 16 — Large Chamber Electron Beam Welding Machine

Cooling rate is a function of the rate of energy input, material thermal properties, and workpiece thickness. Cooling rate is related to the weld width (Reference 5) which is constrained by the joint gapping considerations. Calculations of energy input must account for the fraction of the incident beam energy converted into heat within the workpiece. In keyhole-mode welding, a significant portion of the incident beam passes through the cavity (overpower energy), and does not transmit its energy to the workpiece. Some additional portion of the incident beam energy is lost through spatter and back-scattered electrons. The following empirical relationship appears to give a satisfactory value of energy input, E_T , in thick section welds:

$$E_T = E_B - 1.25 E_C \quad (\text{Eq. 2})$$

where:

E_B = Total beam energy

E_C = Overpower energy

Postweld heat treatment, which is required by most codes, usually improves the fracture toughness of structural steels. Excellent toughness properties are developed in the Cr-Mo steels,

(Reference 2) and in the C-Mn steels (Reference 6) after appropriate postweld stress relief treatment. Certain microalloyed steels containing niobium or vanadium, or both, are embrittled by postweld heat treatment. Several investigators have shown that, to ensure freedom from embrittlement with postweld heat treatment, the niobium content must be held to 0.015-0.025% in C-Mn-Nb steels (Reference 7).

Thick-section welding of titanium alloys has been demonstrated in up to 4 in. (100 mm) thick sections (Reference 8). The fatigue strength of electron beam welds in titanium alloys is satisfactory when they are free of defects. Proper chemical composition, cleaning, welding parameters, and postweld stress relief combine to give good toughness and fatigue characteristics. Welding procedure tests must be conducted in order to verify the titanium composition, the welding parameters and the stress relief treatment for the application.

Thick-section girth welds are frequently electron beam welded. The weld overlap area becomes a problem in these cases. In order to terminate continuous welds, the beam current is downsloped until penetration ceases. The focal spot is also moved upward by sloping the focus

coil current. This helps to reduce weld defects in the overlap area.

The electron beam can penetrate the full thickness of the workpiece whether a joint is present or not. Therefore, repair welding is frequently accomplished by rewelding the joint, eliminating the necessity of grinding out defects. Multipass welding of one to three passes has little or no effect on the mechanical properties of the welded assembly. Under appropriate welding conditions, multipass welding up to five passes does not generate weld defects.

Transverse shrinkage increases approximately linearly for each additional pass (References 9, and 10). Transverse shrinkage per pass is characteristically small. For example, after electron beam welding a 400 in. (10 m) diameter barrel section of 3 in. (75 mm) thick 304L stainless steel using welding parameters producing a 0.2 in. (5 mm) wide weld, the axial shrinkage was 0.03 in. (0.75 mm). Although less shrinkage is helpful, the decreased distortion from EBW is a more significant advantage in most thick section designs.

7.6 Welding Dissimilar Thicknesses. When electron beam welding thin to thick sections, the rules used for thin section welding generally apply. The EBW process is well-suited for the successful fabrication of dissimilar thickness joint designs. The production of satisfactory welds is dependent on three variables:

- (1) Joint design
- (2) Assembly fixturing
- (3) Material properties

Some common examples where dissimilar thickness joints are found include bellows, heat exchangers, and diaphragms.

7.6.1 Joint Design. Proper joint design is the most critical step when producing a weld between metals of dissimilar thickness. Due to the relative rigidity of the thick member, the effects of solidification shrinkage and residual stresses on the thin side of the weld joint must be considered during the design stages. Many failures are avoided if the thin member is loaded to reduce tensile stresses across the weld metal during the weld thermal cycle.

The strength of the finished weld joint is increased by designing with lap, step, or standing edge joints, as shown in Figure 17. These designs all provide excess base material. This acts as filler metal, to reduce weld discontinuities, and enhances the bridging of molten weld metal between

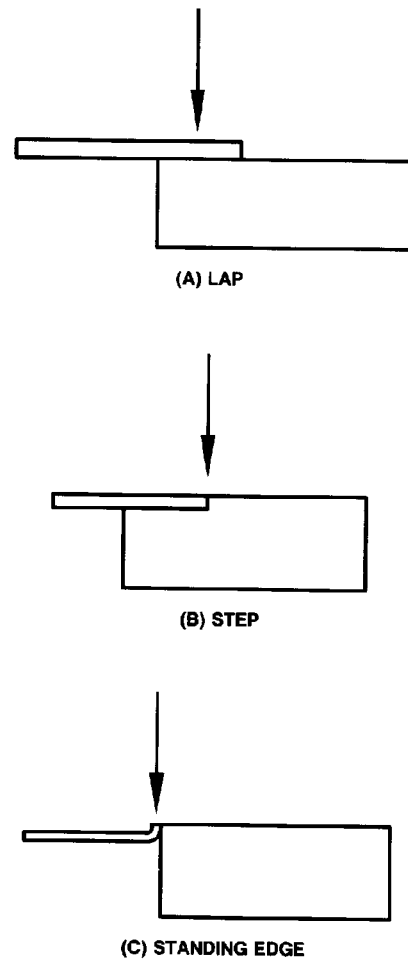


Figure 17 — Thin-Section-Weld Joints

parts. Lap, step, and edge designs handle loading well as they tend to transfer, or spread, the stresses within the structure to points away from the weld area (Reference 11).

Butt joints and T-joints are the least desirable joint configurations for dissimilar thickness welding. These designs may not allow adequate wetting to occur in some alloy systems, causing the weld fusion zone to not coalesce. Poor joint tolerances inherent in these designs increase the chances for missing the joint with the electron beam, so part and fixturing tolerances must be held extremely tight. The butt and T-joint designs also ensure that the finished weld joint has the lowest load bearing capability in the structure (Reference 12).

7.6.2 Assembly Fixturing. The design of assembly fixturing is an important step in controlling welds between dissimilar thickness sections. Part mismatch, uneven heatsinking, uneven preheating, and poor joint alignment, are often caused by poor fixturing design. Proper heatsinking and the removal of part mismatch are usually solved with the same fixturing. Part mismatch and joint runout easily change a step joint into undesirable configurations such as butt joints or, in severe cases, bead on plate, as shown in Figure 18. If heat buildup is a

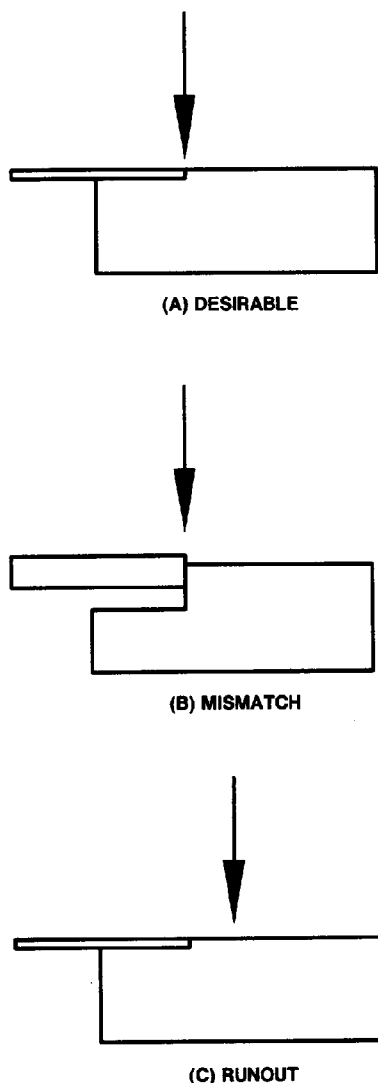


Figure 18 — Mismatch and Runout Problems

problem in the thin section, well-designed fixturing doubles as assembly fixturing and heatsinking. In cases where preheating is necessary, lack of uniformity in the preheat temperature along the weld joint may be caused by fixturing that does not adequately hold the joint together.

Joint alignment is always a concern when electron beam welding. The small diameter of the electron beam allows very little error in beam placement with respect to the joint. Joint alignment is even more critical when welding sections of dissimilar thickness because the thermal properties of the joint change greatly with relatively small deviations in part fit-up.

The part fit-up tolerances should be limited to 10% of the thin member thickness in the assembly to be fabricated. During the design phase, it must be remembered that these tolerances are not only due to the joint gap and joint runout. The total joint deviation also includes the buildup of tolerances from assembly fixturing. The total variation demands that extremely tight machining tolerances be maintained on both parts and fixturing. The importance of proper fixturing is magnified due to the additive nature of these variations (Reference 13).

7.6.3 Material Considerations. Some material properties dealt with during the fabrication of dissimilar thickness joints include thermal conductivity, solidification properties, coefficient of thermal expansion, and surface tension. Material properties should be considered during the design phase, so that problems during welding are avoided, if possible.

7.6.3.1 Thermal Conductivity. Thermal conductivity is a problem in two sets of circumstances. One troublesome area is with high-conductivity materials such as aluminum and copper alloys. Maintaining a molten weld pool in the thick section, while at the same time controlling the degree of superheating in the thin section proves difficult. The high thermal conductivity causes thermal gradients, which in turn may cause surface tension variability. The finished weldment may exhibit unfused areas due to poor metal flow and wetting while welding. Different methods are used to alleviate high thermal-conductivity problems. A decrease in the temperature gradient is achieved by either preheating the thick member or heatsinking the thin member. The thin member must be fully heatsunk, however, or problems may still occur in an erratic manner (Reference 14).

Low thermal conductivity materials have heat buildup problems in the thin section. The heat buildup causes the material slightly ahead of the beam to melt prematurely. The electron beam welding process is excellent for these types of materials since minimal heat input and rapid travel speeds are common to the process. These process characteristics act to reduce the conduction melting at the leading edge of the weld which is typical of most other welding processes.

7.6.3.2 Solidification Properties. The solidification properties are a function of many aspects of the material properties. The high solidification rates found in EBW may either help, or hinder, a particular material to be welded satisfactorily. The first guide to the prospective weldability is the equilibrium phase diagram for the major constituents in the alloy. Although the solidification of weld metal is not an equilibrium cooling condition, phase diagrams give insight as to the size of the alloy "mushy" zone during solidification. The temperature range and concentration gradients within the mushy zone indicate the ability of the welded section to withstand, without cracking, weld shrinkage during postweld cooling.

The high solidification rates associated with EBW are a problem for those materials sensitive to high strain rates and shock loading. Alloys which have major crystallographic restructuring during phase changes (which occur during cooling) may crack due to high residual stresses. These residual stresses are created by the steep temperature gradients associated with EBW.

Joint cleanliness is also important to the solidification properties as hydrocarbons, oxides or other residues become part of the weld metal. Residues may alloy into the weld metal to form brittle or low melting-point phases, or in the case of low-solubility elements, become trapped at grain boundaries or in weld discontinuities. The small amount of molten material present in the fusion zone of an electron beam weld for dilution of these contaminants may not be large enough to stop detrimental conditions such as hot or cold cracking.

7.6.3.3 Coefficient of Thermal Expansion. The coefficient of thermal expansion is a concern if: the joint is constrained during welding, the shrinkage changes the remaining joint geometry, or a dissimilar metal combination is being welded. Residual stresses found in a restrained joint configuration can be very large. Loading on the thin

member, or across a stress raiser in the joint area, causes plastic deformation or material failure when electron beam welding dissimilar thickness sections. Proper fixturing designs transmit either no constraint or a slight compressive load across the weld joint. The welding parameters used should leave no stress raisers such as nonspherical weld discontinuities or lack of penetration defects.

7.6.3.4 Surface Tension. Surface tension problems are caused by the difference in cooling characteristics of the thin and thick sections. The surface tension is highly temperature dependent. The surface tension gradient usually causes the molten metal from the thick section, which is greatly heatsunk, to flow away from the weld joint toward the cooler thick section and the molten metal on the thin section, which has a large amount of superheat, to flow away from the thin section, as shown in Figure 19. These conditions added together cause unfused areas at the weld/base-metal interface due to the nonuniform flow characteristics of the molten metal. The use of lap- or step-type joints with penetration through to the underlying member helps to alleviate this situation.

7.7 Fixturing. Fixturing for EBW is as simple as a C-clamp or as complex and expensive as needed to weld precision joints with high speed and throughput. With EBW, special consideration must be given to the fixturing material, precision and reliability. Fixturing design should also take into account part distortion, part specifications, and welding parameters.

Materials used for electron beam tooling must not add to or develop magnetic fields in the weld region. Avoid electrically insulating the tooling from the weldment (to avoid developing electro-

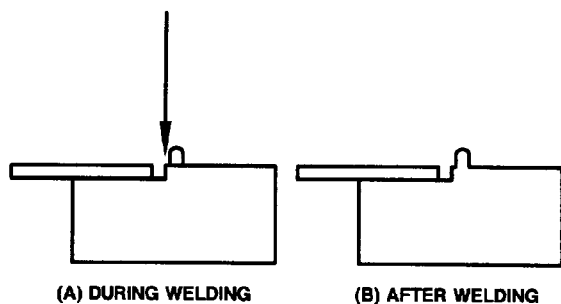


Figure 19 — Effects of Surface Tension

static fields in the weld region). Often, ferritic steels are used in electron beam tooling (for bearings or wear surfaces). When used, they should be degaussed and the residual magnetism monitored.

EBW is an excellent process for the joining of refractory metals and their alloys. Because they have high melting temperatures, the welding power required is generally quite high, and the possibility of excessive heat buildup in the tooling exists. Since contamination of refractories is possible, only refractory metal tooling should be used on contact surfaces. Heat buildup also causes excessive outgassing and distortion in the fixturing which affects focal spot location and joint alignment.

Avoid materials that outgas in the vacuum environment. Tooling and joint designs must be such that tight cavities (which take a long time to evacuate) are avoided or are properly vented.

The need for tooling with very little runout over the length of the weld is noted from the considerations associated with typical weld geometries, as shown in Figure 18. When thin section material is welded in a standing edge joint configuration, it is essential that precision tooling be used. Here it is obvious that very little run out can be tolerated.

Recent developments in seam tracking have served to relax some of the precision needed on fixturing. If seam tracking technology is available, it can reduce fixturing costs on many weldments.

7.8 Controlling Parameters

7.8.1 EBW has more parameters to control than the popular arc welding processes. While this is viewed as a disadvantage by some, the variety of controllable parameters provides the options necessary for EBW to be used for many different applications. As noted in 4.1.4, care must be taken in the control of these parameters, as variations result in significant changes in the finished weldment. Major and minor parameters are reviewed in this section. Minor parameters are not normally used to produce different welding results but should be controlled since they affect the quality of the resulting weld.

7.8.2 Beam Voltage. Beam voltage is a primary welding parameter. As noted in 5.3, EBW equipment comes in a variety of voltage ranges. The range chosen has some effect on the welds produced by the equipment. The beam voltage should be controlled closely because beam power and

beam power density are functionally related to beam voltage. Changes in the beam voltage have a significant effect on the required focus current to produce the minimum focal spot. As noted in 5.4.7, modern fast response solid-state controls hold the beam voltage within 1% of the set value.

7.8.3 Beam Current. Beam current is a primary welding parameter. It is a contributor to both the power input and the power density, although variations in beam current do not have as great an effect on minimum focal spot as beam voltage. An exception to this is found at low beam currents using a hairpin filament. In this case, small changes in beam current have a large effect on the focus current needed to achieve minimum focal spot. In a given application, small changes in beam current have an almost linear effect on weld penetration. This is not true over the full range of beam currents as the actual variation is nonlinear.

Upslope and downslope of the beam power are most commonly accomplished by variations in the beam current. It is therefore necessary to control this through the use of the upslope and downslope time or rate controls. These controls are used during welds which overlap themselves, such as on circular parts. This is necessary to minimize the large lump of material produced during the initiation of the keyhole (upslope) and to gradually close the keyhole after the completion of the weld so that a crater is not left at the completion of weld from the rapid collapse of the keyhole (downslope). It is important that these times are controlled accurately so that the required weld penetration and bead contour are maintained.

7.8.4 Focus Current. The current in the focus coil, is a primary parameter due to its effect on the beam focal spot. This variable has the greatest effect on the power density at the work surface because it changes the area over which the beam power acts. It is imperative that a standard method for determining and controlling the focus current is developed and followed. The focus current is generally referenced to the focal spot on a target located at a gun-to-work distance near that of the work. The focus current at the focal spot is determined at the welding current unless a constant focus gun is used. If a constant focus gun is used, the focus current may be determined at a lower welding current. The use of the lower beam current makes it possible to see the spot size more clearly. It is important to realize that the actual focal point

moves up and down with changes in beam current. When using a lower beam current to determine the focal spot, the beam current used should be recorded with the focus current.

7.8.5 Travel Speed. As with any welding process, travel speed is a primary welding parameter. It determines the power input per unit length of weld, and has a direct effect on weld joint penetration. Like the other primary variables it should be controlled closely to maintain consistency in the welds produced.

7.8.6 Beam Deflection. Beam deflection represents several related controllable parameters. Beam deflection is the result of the oscillation frequency, amplitude, and pattern and phase chosen. Beam deflection is generally used to modify the shape of the weld, but can be used to track a weld joint on a small component.

7.8.6.1 Offset. Beam offset is produced by a DC signal used to position the beam near the joint. This causes an angular deviation of the beam from its normal path. This is useful in some thin section welds or during parameter set-up. Beam offset used in thick section welds may cause the weld to have an incomplete root penetration discontinuity.

7.8.6.2 Oscillation Frequency. Oscillation frequency varies from a fraction of a hertz when using the deflection to generate the weld travel path to thousands of hertz when using beam deflection to modify the weld shape. The oscillation frequency is generally not a major variable when modifying the weld shape, and may be varied 10% in many applications with little noticeable effect.

7.8.6.3 Oscillation Amplitude. Amplitude has a pronounced effect on the resulting weld. It varies the area over which the beam energy is distributed. It should be controlled carefully through visual monitoring and control of the equipment settings. It should be noted that the amplitude varies on some equipment as a function of oscillation frequency.

7.8.6.4 Oscillation Pattern. Oscillation pattern has a significant effect on the weld. Common patterns include circular, sinusoidal (both transverse and longitudinal to the weld travel direction), and elliptical. Modern pattern generators allow numerous complex options. Control of the oscillation pattern is generally done through the control of the

amplitude in orthogonal axes and the input signal and phase to each axis (sinusoid, sawtooth, square).

7.8.7 Gun-to-Work Distance. Gun-to-work distance is another secondary variable. Variations in the gun-to-work distance vary the focal spot, and thus the beam power density. Large changes in the gun-to-work distance have an effect on the minimum focal spot size achieved. The minimum focal spot is achieved at minimum gun-to-work distances. However, short gun-to-work distances are not useful for deep joint penetration welds due to the unusual fusion-zone cross sections, caused by beam divergence, and the large amount of material spattered or evaporated, or both, onto the electron gun.

7.8.8 Vacuum. Vacuum level in the welding chamber has different effects on the welds produced depending on the nominal vacuum level used. In the case of medium vacuum welding, variations in chamber pressure, particularly above 10^{-2} torr (1.3 pascal), have a pronounced effect on the weld penetration and bead shape. This is the result of increased scattering of the electrons by the air molecules. In the case of high-vacuum welding, the effect results in minor changes in the focal spot. In welds requiring high precision, it may be advisable to install a control system which maintains a set high-vacuum level during welding. Any effects of vacuum level are more evident as the gun-to-work distance is increased.

7.8.9 Filament Current. Filament current, when properly adjusted, does not produce a major effect on the weld. EBW equipment has controls to aid in setting the filament current in the proper operating range. If the filament current is operated at a higher current than necessary, the life of the filament is shortened. This also leads to excessive gun discharging or filament destruction. Constant beam geometry and focal size are difficult to maintain when the filament current is too low. It should be noted that the filament kneeing current varies slightly between filaments and with the age of the filament.

7.8.10 Filament Orientation. Orientation is of importance in a limited number of welds. While many welding machines use flat or ribbon filaments which have no obvious orientation, some equipment operates with a "hairpin" type filament made from wire. The beam spot produced by these filaments has a notable elliptical shape. It has an

effect on the resulting weld, particularly when welding a circular part by two axis interpolation of the beam on the workpiece.

7.9 Record Keeping for EBW. Record keeping is mandatory for EBW as it should be for any welding process. Due to the nature of the process and its use in critical or hard-to-inspect locations, very accurate notes of welding conditions should be recorded for later review.

A sample form for recording the EBW parameters is shown in Figure 20. Each individual fabricator may require a different format or procedure for record keeping but the parameters shown on this form are typical.

It is important to use standardized terms and nomenclature so that the information is effectively employed by subsequent users. This type of information is only as good as its accuracy, completeness and readability. It is an important part of an operator's job to properly and completely record the parameters used. Storing such information in a database on a personal computer is a substantial aid in sorting and retrieving the procedural data.

7.10 References

- (1) Binard, J., and Ducrot, A. "Electron beam welding of heavy thicknesses with a 200 W gun." International Conference on Power Beam Technology. Brighton, U.K., 10 - 12 September 1986.
- (2) Farrell, W.J. *A portable 100 W electron beam welding system for pressure vessel fabrication*. Special Technical Publication 755. Philadelphia: ASTM, 1982.
- (3) Kita, H., Nakazaki, T., Akutsu, T., and UeHara, T. "A Study of EB Welding of Carbon and Cr-Mo Steels for Nuclear Application"; Bourges P., Blondeau, R., and Cheviet, A. "Properties of Electron Beam Welds in Chromium-Molybdenum Steel"; Bourges P., Blondeau, R., Ducrot, A., and Binard, J. "Properties of Electron Beam Welds in Constructional Steels"; and Wallach, E.R., Ohara M., Harrison, P. L., and Watson, M.N. "Microstructures and Toughness of Electron Beam Welds in Steels." International Conference on Power Beam Technology. Brighton, U.K. 10 - 12 September 1986.
- (4) Kihara, H.; Minehisa, S.; Sakabata, N.; and Shibuya, Y. "High power electron beam welding of thick steel plates — method for eliminating beam deflection caused by residual magnetism." *Welding in the World* 22(516), 1984.
- (5) Blakely, P. "The Measurement, Control and

Effects of Electron Beam Weld Thermal Cycles; and Tanaka, J., Kosuge, S., and Kunisada, Y. "Toughness of Electron Beam Weld Metal of Carbon and Low Alloy Steels." Third International Colloquium on Welding and Melting by Electron and Laser Beams. Lyon, France, 5 - 9 September 1983.

(6) King, J. F.; David, S.A.; Sims, J.E.; and Nasraddin, A.M. "Electron beam welding of heavy-section 3CR-1.5Mo alloy." *Welding Journal* (7), 1986.

(7) Punahou, C.S., and Elliot S. *The toughness of electron beam welds in thick section C-Mn and microalloyed steels*. Cambridge, England: The Welding Institute.

(8) Shunoyama, T.; Uratani, Y.; Tankano, G.; and Kuri, S. "Study of weldability of electron beam welding for thick plate of austenitic stainless steel," Report 1. *Transactions of Japan Welding Society* 14 (2): 10, 1983.

(9) Arata Y, et al. *Research on fabrication procedure of spherical pressure hull made from titanium alloy for deep submergence research vehicle*, IIW Doc. IV-416-86. The International Institute of Welding, 1986.

(10) Kihara, H.; Arita, K.; and Numata, A. "A study on high power electron beam welding," Report 2. *Mechanical Properties and Some Characteristics of Heavy Section Steel Welds in Pressure Vessels*, IIW/IIS Doc. 766 - 83. The International Institute of Welding, 1983.

(11) Lyman, T., ed. *ASM metals handbook on welding and brazing*, Volume 6, 8th Edition, p. 536. Metals Park, OH: American Society for Metals, 1979.

(12) ASM. *ASM metals handbook on welding, brazing, and soldering*, Volume 6, 9th Edition, Ed. E. F. Nippes, 615 - 617. Metals Park, OH: American Society for Metals, 1986.

(13) American Welding Society. *Welding handbook*, Volume 3, 7th Edition, Ed. W. H. Kearns, 196. Miami, FL: American Welding Society, 1980.

(14) Schwartz, M. M. *Metals joining manual*, 1 - 37 and 43. New York: McGraw-Hill Book Company, 1979.

8. Inspection and Testing of Welds

8.1 Introduction

In the process of establishing an EBW application, it is important to define the critical or desired properties of the electron beam welded joint. These properties are used to determine the appropriate

Customer (Name, Org.) _____ Part Name _____

Charge No. _____ Part No./Qty. _____

Target Date _____ Dwg. No. _____

Completion Date _____ Specification _____

Completed by _____ Matl. 1/thkness _____

Leak Test _____ Matl. 2/thkness _____

Instructions _____

Requirements _____

Cautions _____

System S/N _____ Gun S/N _____ Fixture _____

Gun-to-work _____ Sharp Focus Setting _____ Program Name _____

Beam Voltage (kV) _____

Beam Current (mA) _____

Travel Speed (ipm) _____

(°/min) _____

(s/rev) _____

Weld Focus Setting _____

Filament Current (A) _____

Slope, Up (s) _____

Overlap (s) _____

Down (s) _____

AC Deflection, mode _____

frequency (Hz) _____

amplitude _____

Pulsation, width _____

frequency _____

Fixture Angle _____

Vacuum Level _____

Notes: (Matl. prep, fit-up, abnormalities, special tooling, appearance)

Joint Schematic:

Figure 20 — Electron Beam Welding Record

inspection processes and testing methods. A general overview of appropriate inspection techniques for welding is found in AWS B1.10 *Guide for the Nondestructive Inspection of Welds*. The specified properties are also used to determine practical acceptability limits for discontinuities detected in electron beam welds.

In any case, the inspection methods selected for use and the corresponding acceptability limits should be commensurate with the nature of the service conditions of the weldment. Excessive inspection of a weld joint adds unnecessary costs to the final product whereas insufficient inspection results in the failure to detect weld discontinuities that may affect the fitness for service of the weldment. Nonetheless, consideration of the weld inspection methods and acceptability limits is a vital part of establishing an electron beam welding application in terms of reliability of the weld joint, cost of the product, and length of the manufacturing cycle.

8.2 Weld Characteristics. In order to provide an overview of the various inspection and testing methods, it is appropriate to first define the weld characteristics that affect the service of an electron beam welded joint. The various characteristics can be categorized as geometric features or weld discontinuities.

Features of electron beam welds that are geometric in nature include: weld reinforcement or undercut, melt-through, mismatch, weld width at the face and root, and weld aspect ratio. These features affect the load-carrying capability of the joint as well as fatigue strength and the amount of distortion. The types of discontinuities found in electron beam welds are the same as most other fusion welds. Included among the types of weld discontinuities are linear indications or cracks (both surface and subsurface), porosity, cold shuts, inclusions, undercut, incomplete fusion, and incomplete joint penetration.

In applying the EBW process and selecting inspection methods, it is necessary to specify limits for the discontinuities that affect the joint's fitness for service and, hence, render the discontinuities as defects. It is also important to verify that the sensitivity of the inspection processes and techniques selected are adequate to detect the size of discontinuities deemed unacceptable.

8.3 Inspection Processes. The types of inspection and testing methods used for welded joints are generally classified as destructive or nondestructive.

8.3.1 Destructive Inspection. Destructive testing methods, such as metallographic examination are used in conjunction with nondestructive testing processes to establish specific testing techniques and to verify the capability of the nondestructive testing processes. Metallographic examination of weld cross sections is used to measure weld-fusion-zone geometry and characterize the weld microstructure.

8.3.2 Nondestructive Inspection. The types of nondestructive inspection processes commonly used for electron beam welds include visual inspection (VT), penetrant inspection (PT), radiographic inspection (RT), ultrasonic inspection (UT), and magnetic particle inspection (MT). Each of these processes has advantages and limitations. A short discussion of these processes follows.

Visual inspection is probably the most common inspection method used in the industry. Visual inspection is normally used to measure geometric weld features such as reinforcement, melt-through, undercut, weld width and mismatch. It is also used to detect defects such as incomplete fusion, incomplete joint penetration, and some linear indications. Visual inspection is used on nearly every electron beam weld, and may be the only inspection method employed for noncritical weldments. Visual inspection is also a very common in-process inspection method.

Penetrant inspection is capable of detecting exposed surface discontinuities. The PT process is relatively economical and the sensitivity can be varied depending on the type of penetrant and emulsifier used. The process is normally used to inspect electron beam welds in sheet materials with low to moderate joint stresses. It is also used as an in-process inspection method prior to and after heat treatments.

Radiographic inspection is used to detect both surface and subsurface discontinuities but is used primarily for the detection of subsurface discontinuities. Radiography is used for the inspection of moderately to highly stressed joints or for inspection of porosity/cold-shut content in the weldment.

Ultrasonic inspection is a testing method capable of detecting both surface and subsurface discontinuities. As a result of the cost and the high level of operator skill required, ultrasonic inspection is usually reserved for critical or highly stressed joints and thick section welds. The ultrasonic inspection process has an advantage over radiographic inspection in that it is more capable of

detecting discontinuities that cannot be detected with RT because of their orientation.

Magnetic particle inspection is another process capable of detecting surface and local subsurface discontinuities. This process is only used on ferromagnetic materials. The magnetic particle inspection process is usually used to inspect moderately stressed electron beam welds, and the size of the welded assembly often limits the application of the process.

The selection of these and other inspection processes depends largely on the materials being welded, service condition of the joint, size and location of the joint, the economics of the process, and the requirements imposed by the customer.

8.4 Special Inspection Techniques. With reference to the above mentioned inspection processes, there are several special inspection techniques that are unique to EBW. One technique is that of the black-line x-ray. Application of the EBW process requires weld joints with very tight fit-ups. The tight fit-up assists welding but can also make it difficult to interpret radiographs of weld joints that might contain an incomplete fusion discontinuity. Thus, in order to provide a comparison standard for the inspection of the radiograph, an electron beam joint that has been tack welded together is radiographed. This black-line x-ray is then used by the inspector to interpret radiographs of welds that might contain a cold-shut or incomplete fusion discontinuity.

Another common technique is the use of radiographic windows. This entails placing a machined groove or "window" at a certain level of weld joint penetration. The weld is acceptable if the groove is not shown by radiography and therefore assumed to have been filled during welding.

A technique used to assist the visual inspection of electron beam welds is that of witness features. Witness features are often used on concealed joints or weld joints where it is difficult to verify joint consumption by the weld. The most common type of witness feature in use today is that of witness lines.

Witness lines are scribed or machined lines located on both sides of the joint to be welded. The lines can be located on the face side or the root side of the joint depending on the joint design and the accessibility to the weld joint. Witness lines can be categorized as consumable or nonconsumable. With consumable witness lines, the centrality of the weld relative to the joint is verified by the complete consumption of scribe lines on both sides of

the joint by the weld. Likewise, nonconsumable witness lines are used by verifying the centrality of the weld between the two scribed lines on both sides of the joint.

Other witness features include the use of grooves or lips adjacent to the weld joint. With the distance from the feature to the weld joint being known, the centrality of the weld is verified by making measurements from the weld centerline to the witness feature and comparing the measurement to the known distance.

Another method of inspecting electron beam welds in terms of joint consumption is that of the minimum weld width. This is done by specifying a minimum weld width on the basis of the joint thickness and achieving the minimum weld width during parameter development. The minimum weld width is then used in conjunction with a maximum allowable joint run-out to establish a level of confidence that the joint is completely fused.

A technique commonly used in the inspection of hermetically sealed assemblies and pressure vessels is that of leak testing. There are a variety of testing methods used to inspect electron beam welds for cracks, voids, or any other discontinuities that affect the integrity of a hermetic seal. Among these are leak testing by pressuring welded assemblies with fluids, bubble testing, flow testing, and testing with specific-gas detectors. One common specific-gas-detector type is helium leak testing. There are several different methods capable of detecting helium or any other gas that might leak from a defective weld.

Each EBW application is different and the appropriate inspection methods depend on the materials being welded, size of the assembly, and service conditions of the joint. Nonetheless, close communication between the design, manufacturing, and inspection sources helps in selecting appropriate inspection processes and practical acceptability limits.

8.5 Acceptability Limits. An important aspect of incorporating EBW into the fabrication of a product is the specification of acceptability limits. These limits are specified by the designer of the product based upon the nature of the service that the product will experience. However, establishing practical limits of acceptability for weld discontinuities requires a knowledge of the discontinuities inherent of a given process/material combination. For example, heat-affected zone microfissures are common in certain precipitation hardenable nickel-base alloys. Also, a certain level of porosity

can be expected when welding materials with high levels of dissolved gas, such as the nitrogen-strengthened stainless steels. Thus, it is important to specify practical limits for these types of discontinuities.

Acceptability limits are required for weld discontinuities such as linear indications, voids, undercut, underfill, incomplete joint penetration, and incomplete fusion. These limits are specified on an engineering drawing of the finished product, in a process specification, or in a legal agreement between the designer and the manufacturer. Certificates of conformance are the responsibility of the manufacturer upon completion of the welding and inspection of the product.

8.6 Inspection Plans. The sequence for establishing an EBW process application is further described in section 12. It should be noted that the various types of weld inspection and testing follow the process-development sequence. The fabricator should establish inspection plans during process development.

The inspection plan should document the type of inspection processes to be used with the various inspection methods and the frequency of application. The types of testing include preproduction or initial qualification, individual-part testing, and periodic testing. The engineering requirements of the welded parts determine if individual-part inspections are required or whether periodic inspections are appropriate.

9. Equipment Maintenance Program

A good preventive maintenance program plays a vital role in producing consistent performance and minimizing unexpected, costly, breakdowns. EBW equipment is no exception. An adequate stock of replacement parts and a periodic inspection and maintenance program are a necessity for ensuring maximum machine performance and dependability. Also, the high replacement cost of EBW equipment dictates that extending the life of existing machines is an economic necessity.

The preventive maintenance program described in this section is typical. Of course, the preventive maintenance program for each machine must be custom tailored, based on the manufacturer's recommendations and the specific machine components.

9.1 Preventive Maintenance Performed Daily

- (1) Check oil level in all mechanical vacuum pumps and blowers.
- (2) Remove debris from tooling components and chamber interior.
- (3) Be sure oil in high-voltage tank is at proper level.
- (4) Check oil level and pressure on air filter-lubricator unit.
- (5) Inspect all hoses and connections for oil or water leaks.
- (6) Check to be sure there is sufficient cooling-water flow to diffusion pump.
- (7) Check diffusion pump oil level.
- (8) Leak-check the dynamic or frequently broken static vacuum seals.
- (9) Clean the door seal area of debris.

9.2 Preventive Maintenance Performed Weekly

- (1) Clean external surfaces of all blowers and mechanical pumps.
- (2) Inspect anode and grid. Polish out any scratches using metal polish. Use lint-free wipes with solvent to clean all parts.
- (3) Thoroughly clean the inside of the chamber. (A common practice is to coat the clean chamber surfaces with a film of liquid hand soap. The soap film is left on the surfaces until the next cleaning. At that time, the surfaces are washed with clean water and recoated. The soap does not seem to affect the evacuation time or otherwise impair the process.)
- (4) Using an ohmmeter, check for zero resistance from tip of voltage shorting probes to earth ground.
- (5) Inspect all doors and access port seals (o-rings) for damage.
- (6) Clean with lint-free wipes and relubricate with light coat of vacuum grease. If in doubt about condition of seal, replace it.
- (7) Measure and record the evacuation time to "vacuum ready" status and the rate-of-rise with a clean, dry, empty chamber.
- (8) Perform an operational reproducibility demonstration.
- (9) Replace or clean window liner glass.
- (10) Check all tooling and fixturing for magnetism.

9.3 Preventive Maintenance Performed Monthly

- (1) Inspect high voltage cable and cathode insulator pins for wear. Look for discoloration/particulate/arcing in cathode insulator oil.
- (2) Check high voltage tank receptacle oil for dis-

coloration/particulate/arcing. Inspect high voltage cable and pins for wear.

(3) Inspect all hoses, cables, and connections for wear.

(4) Vacuum all cabinets. Clean all heatsinks on internal modules. Clean all air filters and louvers.

(5) Check the phase balance on the three-phase electrical system.

9.4 Preventive Maintenance Performed Quarterly

(1) With a clean graduated beaker, drain oil from the cold diffusion pump.

Record the amount of oil drained, and if it is reusable, refill the pump, adding oil if necessary.

(2) Inspect motor brushes for wear and fit. Replace if necessary.

(3) Check all interlocks and safety switches for proper operation.

(4) With a high voltage oil tester, measure and record the dielectric breakdown point of the high voltage tank oil.

(5) Check for infinite resistance between high-voltage pins using a 1000 VDC megohm meter. Inspect all pins and sockets for wear.

(6) Check optics for alignment. Adjust if necessary.

(7) Inspect filters in water inlet line to diffusion pump. Change them if they show signs of clogging.

(8) Measure and record the ripple content of the outputs of the alignment, deflection, and focus supplies using an oscilloscope.

(9) Use a Faraday cup to measure and record the values of beam efficiency, beam stability, and proper operation for the up slope and downslope functions.

(10) Drain, flush and replace the oils in all mechanical vacuum pumps and blowers.

(11) Inspect integrity of all ground cables. Reading to ground points should be zero ohms.

(12) Calibrate high voltage metering circuitry.

(13) Use a storage oscilloscope or strip chart recorder to check operation of the high voltage ramp module.

(14) Calibrate vacuum metering circuitry.

(15) Calibrate oscilloscope, check for proper operation of deflection generator. Make adjustments if required.

9.5 Preventive Maintenance Performed Semiannually

(1) Survey entire electron beam system for radiation leakage. Record amount and location of leaks. Repair leaks before proceeding.

(2) Check for loose connections, arcing and damage in the high voltage tank.

(3) Check the power-supply-overload trip settings. Adjust if required.

(4) Check the high voltage spark gaps for cleanliness and proper settings. Clean and adjust as required.

(5) Clean or replace the optical elements, as necessary.

10. Standards and Specifications for Electron Beam Welding

10.1 Introduction. This section presents a listing of the standards and specifications, at the time this document was prepared, associated with the EBW process. Several of the abstracts are similar because the scope and applications of these specifications and standards are quite broad.

This listing was compiled by reviewing standards and specifications issued by government and national organizations associated with industry. The majority of the standards and specifications address the aerospace industry and were established by either the government (military) or the Society of Automotive Engineers (SAE). Only those specifications written and published in the United States have been included in this text.

10.2 Standards and Specifications. The following abstracts are divided into several groups based on the issuing organization of the standard or specification. Each abstract gives the standard or specification number, affiliated organization, and a review of the major topics discussed. A convenient cross reference chart is shown in Figure 21, to aid the reader in determining which specifications are of interest.

10.2.1 Military Standards and Specifications

(1) MIL-W-46132(1) *Welding, Fusion, Electron Beam, Process For*, Department of Defense

This specification covers the general requirements for the electron beam fusion welding process for use by all Departments and Agencies of the Department of Defense. Qualification requirements for the equipment, operator, and welding procedure are outlined. Joint designs and fit-up tolerances for various material thicknesses are also given. Both similar and dissimilar weldments of unlimited thickness are permitted, with the follow-

	Military				SAE						ASME		AWS			Misc
	MIL-STD-453C	MIL-W-46132	MIL-W-80119	MIL-STD-1595	NAS-976	ARP-1317	ARP-1333	AMS-2635	AMS-2680	AMS-2681	Section IX	AWS-B2	AWS-F2.1	AWS-D14.2	Y-DA-6352	
1.0 Acceptance Standards	X	X	X		X	X	X		X	X	X	X		X	X	
2.0 Equipment																
Design and Fabrication			X		X											
Electron Gun			X		X										X	
Electrical Systems			X		X										X	
Installation					X										X	
Instrumentation			X		X											
Packing and Preservation			X		X											
Qualification		X				X			X	X	X	X		X		
Safety Devices			X		X											
Vacuum Systems			X		X											
Warranty					X											
3.0 Filler Materials		X				X			X	X	X	X		X		
4.0 Fixturing and Tooling									X	X						
5.0 Joint Designs and Tolerances		X				X			X	X				X		
6.0 Material Handling and Cleaning						X			X	X				X		
7.0 Material Types																
Aluminum Alloys	X	X		X		X			X	X	X	X				
Cobalt Alloys	X	X		X		X			X	X						
Copper Alloys		X				X				X	X	X				
Iron Alloys	X	X		X		X			X	X	X	X		X		
Magnesium Alloys	X			X		X				X						
Nickel Alloys	X	X		X		X			X	X	X	X				
Refractory Metal Alloys		X				X			X	X						
Titanium Alloys	X	X		X		X	X			X	X	X				
Zirconium Alloys											X	X				
8.0 Operator Qualification	X	X		X		X			X	X	X	X		X		
9.0 Personnel Safety	X					X							X	X		
10.0 Procedure Qualification	X	X		X		X			X	X	X	X				
11.0 Quality Assurance	X	X		X		X	X	X	X	X				X		
12.0 Testing																
Destructive		X		X					X	X	X	X				
Nondestructive	X	X		X		X	X	X	X	X	X	X				
Metallurgical		X		X					X	X		X				

Figure 21 — Cross Reference Chart for Electron Beam Welding Specifications

ing alloys specified; carbon and alloy steels, aluminum alloys, cobalt alloys, copper alloys, molybdenum alloys, nickel alloys, tantalum alloys, titanium alloys, and tungsten alloys. The addition of filler wire is acceptable, with the wire types specified for the various material combinations. Procedures for destructive, nondestructive, and metallurgical evaluation of the weldments are also included.

(2) MIL-W-80119B *Welding Machines, Electron Beam, Vacuum Type*, Department of Defense

This specification covers a general purpose EBW system, designed to focus a controllable source of accelerated electrons into a high energy density beam in a vacuum environment. Requirements for the design, fabrication, and performance of the welding system are given. This includes the weld chamber, vacuum pumps, and all mechanical and electrical devices essential to the system. Optional devices to be specified by the purchaser for specific applications are also outlined.

Quality assurance provisions are given to assure that the performance of the final welding system is acceptable. Specifications for packaging and preservation for shipment of the machine are also listed. This specification is mandatory for use by all Departments and Agencies of the Department of Defense.

(3) MIL-STD-453C *Inspection, Radiographic*, Department of Defense

This standard covers the requirements for radiographic inspection of both metallic and nonmetallic materials, and is not intended to define or control the acceptability or quality of the materials inspected. This standard supersedes MIL-STD-00453B, (USAF), Inspection, Radiographic, and MIL-STD-453 (DOD), Inspection, Radiographic, and is for use by all departments and agencies of the Department of Defense.

This military standard addresses all aspects of the radiography procedure which affect the quality of the image produced. Qualification procedures for the equipment, personnel, and inspection procedure are outlined. Recommendations are given for radiographic equipment type, setup, and parameters. Film and penetrometer types are given, along with exposure and viewing procedures. Allowable limits are specified for the density of the radiograph produced, with quality assurance provisions for recording essential parameters and maintaining records.

(4) MIL-STD-1595A *Qualification of Aircraft, Missile, and Aerospace Fusion Welders*, Department of Defense

This military standard establishes the procedures for the qualification of welders and welding operators engaged in the welding of aircraft, missiles, and other aerospace equipment by fusion welding processes. It is also applicable to the welding of aerospace ground-support equipment when included in the contracting documents or when invoked in the absence of a specified welder qualification document. Qualification of welding operators is determined by the welding process, material type, and material thickness. The following materials are acceptable under this standard; carbon and alloy steels, aluminum alloys, cobalt alloys, magnesium alloys, nickel alloys, and titanium alloys. Qualification can be obtained for unlimited material thickness. The acceptance criteria include destructive, nondestructive and metallurgical examination of the weldments. This standard is approved for use by all Departments and Agencies of the Department of Defense.

(5) MIL-STD-2219 *Fusion Welding for Aerospace Applications*

This standard is intended to replace MIL-W-8604A (1982), MIL-W-8611 (1957), and MIL-W-aZ (1956)

10.2.2 Society of Automotive Engineers Standards and Specifications

(1) NAS-976 *Electron Beam Welding Machine — High Vacuum*, Society of Automotive Engineers

This National Aerospace Standard (NAS) addresses the manufacture, performance, and procurement of an electron beam, high-vacuum system exclusive of welding positioners, manipulators, and other mechanical tooling devices. Requirements for the welding chamber, electron gun, vacuum system, power supply, instrumentation, and safety devices are included. Procedures for the inspection and acceptance of the final welding system are outlined. Preservation, packing, and shipping requirements are given. A brief description of the installation, operation, and warranty procedures is also provided. This standard was established primarily for applications in the aerospace industry. It lists only the minimum requirements and is not limited to design advancements.

(2) ARP-1317A *Electron Beam Welding*, Society of Automotive Engineers

This Aerospace Recommended Practice (ARP) describes techniques to be used for EBW materials commonly employed in the aerospace industry. This is a general specification providing a descrip-

tion of the electron beam process, giving both its advantages and limitations. Guidelines for qualification of the equipment, welding procedure, and operator are listed. Specifications for personnel safety, material handling, joint design, fit-up tolerances, and weld acceptance criteria are also included. Qualifications can be obtained for unlimited material thicknesses, with or without filler additions, using the following alloys; carbon and alloy steels, aluminum alloys, cobalt alloys, niobium alloys, copper alloys, magnesium alloys, molybdenum alloys, nickel alloys, tantalum alloys, and titanium alloys. Nondestructive testing may be required, depending upon the application.

(3) *ARP-1333 Nondestructive Testing of Electron Beam Welded Joints in Titanium-Based Alloys*, Society of Automotive Engineers

This Aerospace Recommended Practice describes techniques for nondestructive evaluation of electron beam welded joints in titanium-based alloys. This specification is valid for material thicknesses up to 2 in. (50 mm) at the weld location. The procedures and acceptance requirements for the following five tests are described; visual, witness line, radiographic, ultrasonic, and fluorescent penetrant. This recommended practice specification has been approved by ANSI.

(4) *AMS-2635C Radiographic Inspection*, Society of Automotive Engineers

This Aerospace Materials Specification (AMS) covers procedures for radiographic inspection. Its application is for determining the presence of weld imperfections that may not be exposed during surface inspection. The specification continues by explaining the quality assurance and identification procedures for acceptable parts.

(5) *AMS-2680A Electron Beam Welding for Fatigue Critical Applications*, Society of Automotive Engineers

This Aerospace Materials Specification (AMS) defines the procedures and requirements for joining various metal alloys using the EBW process. Its application is primarily for high-quality, electron beam welding of aerospace components, the failure of which could cause either significant injury to the occupants of a manned vehicle, or loss of the aerospace vehicle, its major components, or both. Qualification requirements for the welding equipment are referenced to National Aerospace Standard, NAS-976. Specifications for the welding procedure include requirements for the tacking, penetration, and cosmetic passes.

Run-on and run-off tabs are required during

welding. Operator qualification requirements are given, along with specifications for material handling, fixture design, and joint fit-up tolerances. The use of the following materials, with or without filler wire additions, is permitted; carbon and alloy steels, aluminum alloys, cobalt alloys, nickel alloys, and refractory alloys. Acceptance and quality assurance provisions are outlined, with destructive, nondestructive, and metallurgical evaluations used to determine weld quality. Fatigue data is required for each joint design, material type, and weld procedure. This material specification has been approved by ANSI and adopted by the DOD.

(6) *AMS-2681A Electron Beam Welding*, Society of Automotive Engineers

This Aerospace Material Specification defines the procedures and requirements for joining various alloys using the EBW process in both high and medium vacuums. The primary application is for the aerospace industry and those applications not covered by AMS-2680. Qualification requirements for equipment are referenced to National Aerospace Standard, NAS-976. Operator qualification is referred to MIL-STD-1595. Procedures for material handling, fixture design, and joint fit-up tolerances are presented. Welding procedure specifications include requirements for the tacking, penetration and cosmetic passes. The use of run-on and run-off tabs is required during welding. The material types acceptable under this specification are given in the Aerospace Recommended Practices, ARP-1317.

Any alloy combination, heat treatment, and thickness may be used provided a welding procedure is established. This includes the use of filler wire additions. Quality assurance and weld acceptance requirements are given, using destructive, nondestructive, and metallurgical evaluations to determine weld quality. This material specification has been adopted by the DOD.

10.2.3 American Society of Mechanical Engineers Standards and Specifications

(1) *Section IX, Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers

Section IX addresses the qualification of welders, welding operators, and welding procedures employed in work governed by the ASME *Boiler and Pressure Vessel Code* and other work where use of ASME Section IX is mandated by contract documents or referenced in technical specifications such as military standards. Requirements for the

qualification of the operator and welding procedure are given.

The process variables for EBW are divided into three groups; essential, nonessential, and supplementary. Procedures are outlined for the actions required for changes in the process variables, depending upon the group classification. The acceptable base-material types are provided in detail, and are classified under a "P" number system. The following provides a generalization of the major material groups permitted; aluminum alloys, carbon steel, copper alloys, low alloy steel, nickel alloys, titanium alloys, and zirconium alloys. Section IX is referenced by various construction and fabrication codes, such as ASME sections I, III, IV, and VIII, for the qualification of welders and welding procedures. Qualification under section IX is not a guarantee that procedures and performance qualifications are acceptable to a particular construction code.

10.2.4 American Welding Society Standards and Specifications

- (1) AWS F2.1, *Recommended Safe Practice for Electron Beam Welding and Cutting*, American Welding Society

These safe practice recommendations are intended to provide a baseline document for owners and users of EBW and cutting equipment. They provide a minimum standard for protecting personnel and property from the potential hazards specifically associated with electron beam applications. In general, these recommended safe practices are applied to electron beam heat treating, electron beam curing, electron beam metal deposition, etc. The four following potential hazards are outlined and discussed in detail within this specification; electrical shock, x-radiation, fumes and gases, and visible radiation.

- (2) ANSI/AWS D14.2, *Specifications for Metal Cutting Machine Tool Weldments*, American National Standards Institute, American Welding Society

The purpose of this specification is to establish practices for the design and fabrication of machine tool structures and components. Requirements for welding and repair of machine tools and machine tool structures are presented. The allowable base materials consist of the following; low alloy steels and AISI 304L and 316L stainless steels. Filler-wire types, when required, for the above alloys are given. Joint designs are discussed, with the allowable unit stresses provided for fillet and groove

welds. Material preparation and assembly guidelines are listed. Quality assurance and acceptance standards for workmanship are also provided. The electron beam process is acceptable when a pressure vessel is attached or incorporated into the machine tool being fabricated. Under this provision qualification of the operator and welding procedure is to be in accordance to Section IX of the *ASME Boiler and Pressure Vessel Code*.

- (3) ANSI/AWS B2.1, *Standard for Welding Procedure and Performance Qualification*, American Welding Society

This standard provides requirements for the qualification of welding procedures, welders, and welding operators. The process variables for EBW are divided into two groups; welding variables (which must be addressed by the written welding procedure) and qualification variables (which if a change is made from the variable qualified, would require requalification of the procedure). B2.1 covers all common construction materials, including most of those listed in ASTM, SAE, and Canadian standards. It is used when invoked by the referencing fabrication code or contract.

10.2.5 Miscellaneous Industry Standards and Specifications

- (1) Y-DA-6352, *Electron Beam Filament Specification and Gun Contours*, D.G. Scott, Oak Ridge Y-12 Plant

This specification was adopted from a paper presented at the SME Welding and Brazing workshop, Chicago, Illinois, October 28 - 30, 1975. Provided is a specification for the filament assembly of a high voltage electron beam gun. Dimensional and surface finish requirements are given. Installation and testing procedures are also outlined. Also included in this article, separate from the filament specification, is information on focus current variations resulting from different grid cup contours. This specification can be purchased from the National Technical Information Service (NTIS).

Copies of the specifications and standards mentioned above can be obtained from the following addresses:

- (1) U.S. Government Publications — Standardization Document Order Desk, 700 Robbins Avenue, Bldg. #4, Section D, Philadelphia, PA 19111.
- (2) Society of Automotive Engineers (SAE) — 400 Commonwealth Drive, Warrendale, PA 15096.
- (3) American Society of Mechanical Engineers

(ASME) — United Engineering Center, 345 East 47th Street, New York, NY 10017.

(4) American Welding Society (AWS) — 550 N.W. LeJeune Road, P.O. Box 351040, Miami, FL 33135

(5) National Technical Information Service (NTIS) — 5285 Port Royal Road, Springfield, VA 22151.

11. Training and Qualification of Operators

This section outlines training procedures necessary to qualify an EBW operator. Upon completion of the preliminary training, a qualification test assembly is welded. When inspection of the test weldment shows satisfactory results, the operator is qualified to make electron beam welds on this category of production assemblies.

11.1 Electron Beam Welding Equipment Operation. The operator should be trained in the following areas of equipment operation. (Note: The following items are not common to all EBW machines, and those items which are not applicable should be omitted.)

11.1.1 Equipment Start and Stop. The operator should be able to start up and shut down the EBW machine including both temporary and extended time shut-down.

11.1.2 Vacuum System. The operator should be able to find and inspect all points of preventive maintenance such as oil sight glasses. The operator should show an awareness of the proper sequencing of the valves and the damage caused by improper sequencing. The general purpose of each major component in the system must be understood so that the direction of air flow through each element of the system during each phase of the vacuum control cycle can be explained to the examiner.

11.1.3 Table and Fixtures. The operator should be able to perform all table movements as required for normal operation with proper operation of the system interlocks and the connection of electrical control cables.

11.1.4 Work Set-up. The operator should be able to exchange work fixtures. The operator

should be able to place fixtures in the proper orientation inside the machine.

11.1.5 Chamber Seals. The operator should be able to demonstrate knowledge of vacuum chamber closure and proper care of vacuum chamber seals. Where applicable, the operator should show that he or she can properly remove any "O" ring seals, clean both seals and sealing surfaces, apply vacuum grease as required, and reassemble all seals.

11.1.6 High Voltage System. The operator should be able to demonstrate an understanding and safe working knowledge of the high voltage system. The operator should show awareness of the source of the high voltage power involved, the magnitude of the voltage, and the cable which carries this power to the electron gun. The operator should understand the importance of such safety devices as the static discharge probe and the reason for turning off any motor-generator-type power source while working on the upper column.

11.1.7 Electron Beam Gun Assembly. The operator should be able to prove a working knowledge of the electron beam gun and filament assembly and should be able to open the upper column or gun assembly, vent the column when necessary, apply all normal safety practices, and service the gun. The operator should be able to properly disassemble, clean, and reassemble all parts. This includes replacement of the filament, if needed, and checking the filament for proper centering and stick-out. The operator should also be able to recognize and replace deteriorated gun components and should be aware of those cleaning materials which are not compatible with the high voltage and vacuum environments encountered in this area.

11.1.8 Anode. The operator should prove an understanding of the purpose of the anode and the importance of maintaining it in proper condition. While the column is open, the operator should inspect and remove the anode from the anode base, clean all surfaces and inspect the upper end for deterioration. If the end of anode appears scored or eroded, it should be repolished or replaced, cleaned, and reinserted into the base. The operator should understand that consistent scoring on one side, or accompanying difficulty with beam alignment indicates the need for an anode alignment check.

11.1.9 Upper Column Maintenance. The operator should demonstrate an adequate knowledge of the proper care and cleaning of the internal surfaces in the upper column. While the bias cup is removed, the operator should remove the corona ring and clean the cathode insulator and inside wall of the column.

11.1.10 Targets. The operator should be able to set up target blocks for beam verification. Where applicable, the operator should demonstrate knowledge of target setting and its relation to beam focus by removing the targets, cleaning up the surfaces and reinstalling them at the proper height to set up the working beam.

11.1.11 Establish Beam. The operator should demonstrate an ability to properly set all required controls and initiate a correctly focused and adjusted beam. The operator should be able to set the required beam voltage and beam current by reference to the panel meters. This includes correctly performing the corona clear sequence and kneeling the filament to the specified beam current drop. The operator should be able to quickly obtain the proper focal spot.

11.1.12 Beam Alignment. The operator should demonstrate a proper understanding of the beam-aligning mechanism. The operator should be able to check the beam alignment and reestablish proper alignment after the beam has been intentionally misaligned by the examiner.

11.1.13 Beam Deflection System. The operator should demonstrate a working knowledge of the beam deflection controls. The operator should be able to set up the frequency of oscillation and the shape, size and location of the beam pattern precisely as required.

11.1.14 Viewing System. The operator should prove a satisfactory knowledge of operating and maintaining the optical or video viewing system. With a properly aligned beam, the operator should properly align the reticle with nondeflected beam by means of the scope or viewer centering adjustment. The operator should be able to recognize major viewing-system alignment problems so that they can be corrected.

The operator should demonstrate to the examiner the proper location of the light beam on the

workpiece and be able to recognize improper alignment. The operator should also remove, clean (or change), and replace the vapor shields.

11.1.15 Computerized Numerical Control (CNC). The operator should be able to demonstrate competence in the use of all required CNC controls. The operator should show that he or she can properly activate the control and switch the machine controls from manual to CNC mode and return. The operator should understand the purpose of protective devices and interlocks, as well as the operational features of the control unit, and prove knowledge of CNC tapes. The operator should be able to select the proper programs on the tapes, set up the tapes, and run the tapes in the numerical control unit.

11.1.16 Radiation Safety Shielding. The operator should recognize the hazards due to x-ray radiation produced during EBW. The operator should demonstrate knowledge of the x-ray shielding incorporated in the machine. This includes removable shields and associated electrical interlocks, leaded glass, and lead panels where used. The need for periodic radiation surveys should be understood.

11.2 Welding Operator Training Program. An initial welding session of simple welds and standard techniques will familiarize each operator with the EBW equipment, process, and its limitations prior to using the process under operational conditions.

11.2.1 Perform specified basic operating procedures such as the following:

- (1) Change the gun filament.
- (2) Corona clear and knee the filament for a given beam current.
- (3) Do beam alignment.
- (4) Set the beam focus.
- (5) Use the deflection system to form simple patterns on a target or test specimen.
- (6) Set the numerical or computer control — if available — for a programmed operation.
- (7) Operate the mechanical part handling systems including run out platforms which load onto the work table.
- (8) Shut down the equipment for both long- and short-term shutdowns.
- (9) Start up the equipment (cold- and warm-starts).

11.2.2 Perform acceptable test welds of basic configurations.

11.2.2.1 Penetration Studies. Using a focused beam and the proper peaked current, make welds on a coupon or test plate. Prior to welding, the test block shall be lined up in the chamber so that the weld will be parallel to the edge of the part. Make development welds on mock-ups of the appropriate joint configuration.

11.2.2.2 Nonvertical Joints. Show ability to tilt fixture, gun, or both, to align the beam to nonvertical joints. Also, weld a blind joint by welding through the base to vertical leg, lining up on ends protruding from each side or along a scribe mark.

11.2.3 Weld Performance Qualification

11.2.3.1 Development Welding. The operator should weld mock-ups of the production-type weld assemblies using the proper welding procedure.

11.2.3.2 Qualification Tests. When the instructor is satisfied that the operator can qualify to the process, qualification specimens are welded per the procedure. Test parts are examined and if satisfactory, the qualification of the welding operator is recorded.

12. Weld Procedure Development for EBW

12.1 Introduction. Due to the attributes of the EBW process such as precise control, cleanliness, and low-heat input fabrication of assemblies, electron beam welding requires the development of weld schedules with more detail and precision than conventional welding processes. The qualification of operators and the testing and inspection of welds are covered elsewhere in this publication, but the process that ties the operator to the schedule spans a range of detail from an operator choosing the appropriate parameters from experience, to a full-scale parametric study used to choose and qualify a welding procedure as a requirement to an extensive quality assurance program. Welding procedure verification as opposed to record keeping is also discussed.

12.2 Choosing Parameters. Welding parameters are typically chosen through experience, "rule of thumb", searching of records, or performing a

parametric study. Experience gained by operators through years of welding often helps in providing satisfactory welding parameters for jobs that do not have extensive requirements, or helps to provide good "ball park" parameters that can easily be tested and modified to suit the job requirements. When the expertise needed to choose a starting point for a weld schedule development is not readily available, certain guidelines can be utilized such as those given in 12.3 and section 13.

Referencing welding records is very useful if they were constructed accurately and utilize standard terminology. Welding results may reproduce poorly when transferred between different machines unless some previous comparisons have been made. Parametric studies are typically performed by applying a range of parameters to a material configuration similar in configuration to that being welded. This method gives more detailed information about the chosen welding parameters and can be applied in varying degrees of detail depending on the requirements of the weld. No matter which of the above methods is chosen, parameter testing is an important step in weld-schedule development.

12.3 Electron Beam Parameter Considerations.

The EBW process and parameter selection offer great versatility when welding to exacting tolerances and for welding difficult materials. On the other hand, if the weld schedule does not include proper parameter control or utilization, the resultant weld may not be optimized for the application or may suffer from repeatability problems. A complete duplication of the weld schedule entails repetition of the welding parameters and adherence to standard practice. An optimized weld schedule utilizes all the control parameters available to satisfy the requirements of the weld. Some control parameter considerations as well as some comments regarding standard practice follow. To best utilize the process, the welding engineer must be familiar with the process capabilities and limitations.

A common starting point is to estimate the linear energy input needed for a particular weld. The linear energy input equation, Eq. 3, although simple, needs careful consideration before application. In general, it is incorrect to use linear energy input as a comparative tool between two systems. However, when comparing two similar systems (high voltage vs. high voltage) energy-input calculations are helpful. The equation used to calculate the beam energy-input, E , follows:

$$E = VI/S^n \quad (\text{Eq. 3})$$

where

E = Beam energy, joules/in. (joules/mm)

V = Beam voltage, kV

I = Beam current, mA

S = Weld speed, in./sec. (mm/s)

n = Material properties term

Although Eq. 3 is correct for conduction mode welding, most electron beam welds are not made using this mode. Therefore, exact matches in linear energy input to penetration using this equation are not to be expected. The exponential term, n , corrects slightly for the welding mode, although other factors must be considered in EBW. To a first approximation, n , a term that is influenced by the material thermal properties, is one, although in reality n has been found to be between 0.4 and 1 for different materials.

Once the approximate energy input is determined, other parameters are exploited to fine tune the finished weld schedule. Beam deflection is used to raster the beam across the joint, along the joint, or both. The most commonly used deflection mode is circular. The frequency and amplitude of this deflection is controlled to distribute the power of the beam over a wide joint area. For example, when using circle deflection, the cross section of the weld is increased thus producing a shallower, wider weld, especially in the root. Wider welds are commonly used to avoid incomplete joint penetration due to improper beam-to-joint alignment and to reduce discontinuities such as porosity and cold shuts. These welds also have smoother roots in partial joint penetration welding and smoother root reinforcement in complete joint penetration welding. One disadvantage of circular deflection is the formation of undercut along one side of the weld in some cases.

Defocusing of the beam is often used in the same manner as deflection to widen the weld. As with deflection, the power of the beam must be increased to obtain similar penetration and the resulting effects of shrinkage and distortion increase. A defocused cosmetic pass is often used to smooth surface irregularities such as spatter, holes and undercut. A slight defocusing of the beam above the weld surface provides improved weld profiles with less tendency to create root voids.

Variations in weld pass sequencing affect the final part both mechanically and metallurgically. When tack weld cracking is a problem, low penetration, complete passes may be substituted. Tack welds may

also adversely affect weld quality and distortion if inconsistent in size and location. Multipass autogenous welds and multipass cold wire feed welds are specialized applications of the EBW process. They require more complex joint designs and equipment and as a result more complex weld schedules.

Other common welding parameters and standard practices which should be maintained from one application of a weld schedule to the next are work height, joint tolerances, cleaning procedures and fixturing.

12.4 Testing of Parameters. Weld parameter testing ranges from performing a weld on the final assembly, basing acceptance on visual inspection, to performing many test welds with detailed examination. In the latter, welding schedule changes continue until the optimal welding procedure is obtained.

A bead-on-plate weld is commonly used as a first step to determine welding parameters, such as beam current, beam voltage, part speed, and focus condition, which produce the required penetration and bead shape. Closer examination of cross sections and top beads provides general information in regard to the occurrence of weld discontinuities such as cracks and porosity.

Joint mock-ups are test coupons of thickness and joint geometry similar to that of the final part. They are typically made from the same material as the final part and are useful in determining the effects of heat flow and joint design. This stage of weld schedule development is used to determine final primary parameters and work height, and secondary parameters such as focus condition. Metallographic inspection verifies that physical, macro- and microstructural requirements of the weld have been met.

Full scale mock-ups of the weldment are used to study the effects of fixture and part distortion on the finished assembly. These parts are also used to set welding time and determine upslope, downslope and overlap times. The mock-ups are useful in setting up nondestructive test (NDT) procedures, and are also used for destructive testing (DT) and proof testing. Computer controlled equipment is programmed and tested on such parts.

Weld qualification samples may be required and are typically full scale mock-ups. They are used primarily to qualify the weld schedule, the operator, and machine repeatability. They usually precede a production run and are performed periodically as part of a quality assurance schedule. They are also repeated in the event of machine maintenance, re-

pair, and/or new operator. NDT or DT procedures are performed on these parts. Statistical analysis of the weld quality should be made on the weld qualification samples. The complexity of this analysis depends on the requirements placed on the weldment.

12.5 Weld Schedule Verification. Once a weld schedule has been optimized and qualified it is ready to be implemented by the operator to produce the desired weld. Accurate storage, retrieval and setup of the developed schedule is required to produce this weld. Calibration of welding equipment should be included in the maintenance of demanding weld schedules. Recent advances in microprocessor control allow storage of many machine parameters that are recalled and run to produce the weld. Computer control helps reduce the possibility of operator error in setup of these parameters but does not reduce the need for adherence to details outside of machine control, i.e. cleaning, material chemistry, tooling, joint preparation, etc. The same attention to detail needs to be

applied when using process monitoring equipment such as strip chart recorders.

13. Practical Examples

Figures 22 through 32 provide various input power levels and travel speeds that may be used to obtain approximate weld penetrations in commonly welded materials. These graphs are only approximate, but provide reasonable starting parameters for each material. The actual curves will vary among the alloys of a given class of materials, but should be similar in shape. To use each graph:

- (1) Find the desired penetration level.
- (2) Draw a vertical line from this point until it intersects with the welding power curve.
- (3) Draw a horizontal line from this point until it intersects with the travel speed axis.
- (4) Parameters to use at the start of development are found at the top of the power curve and along the travel speed axis.

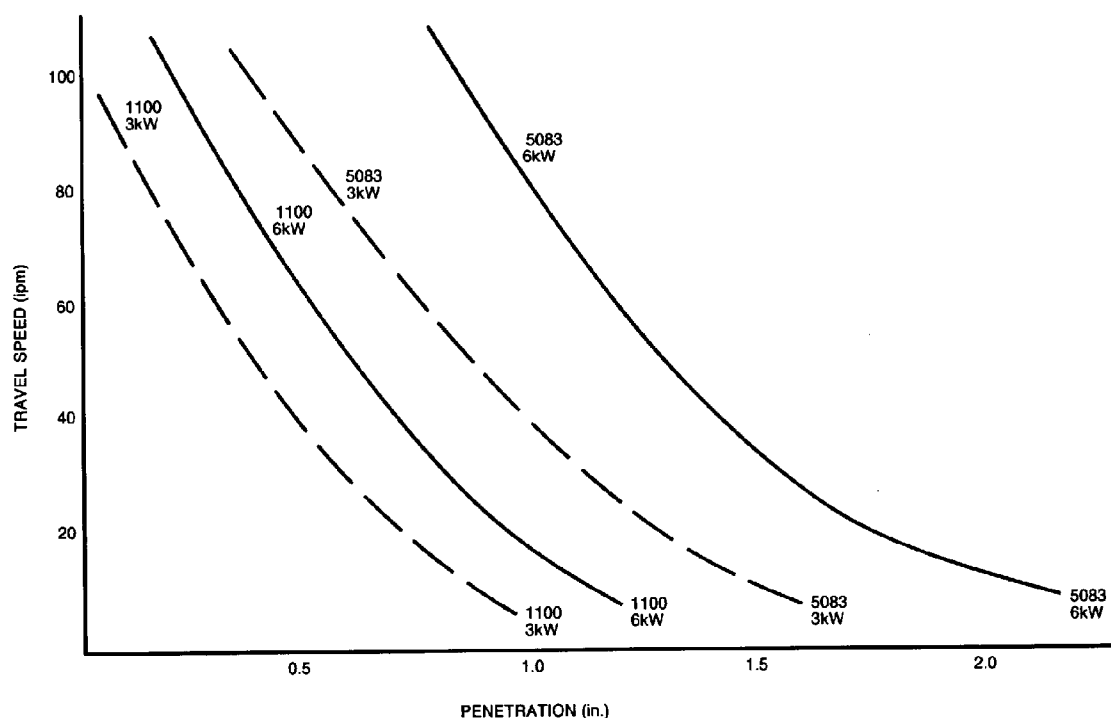
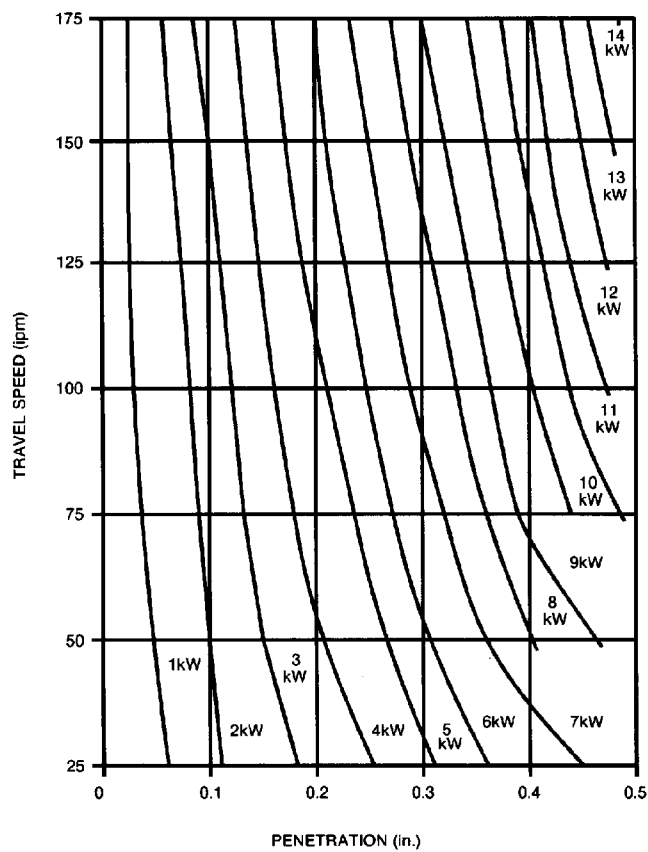


Figure 22 — Power Curves for EBW of Aluminum Alloys



Data taken from a 60 KV system at 10^{-4} torr pressure.

Figure 23 — Power Curves for EBW of Copper Alloys

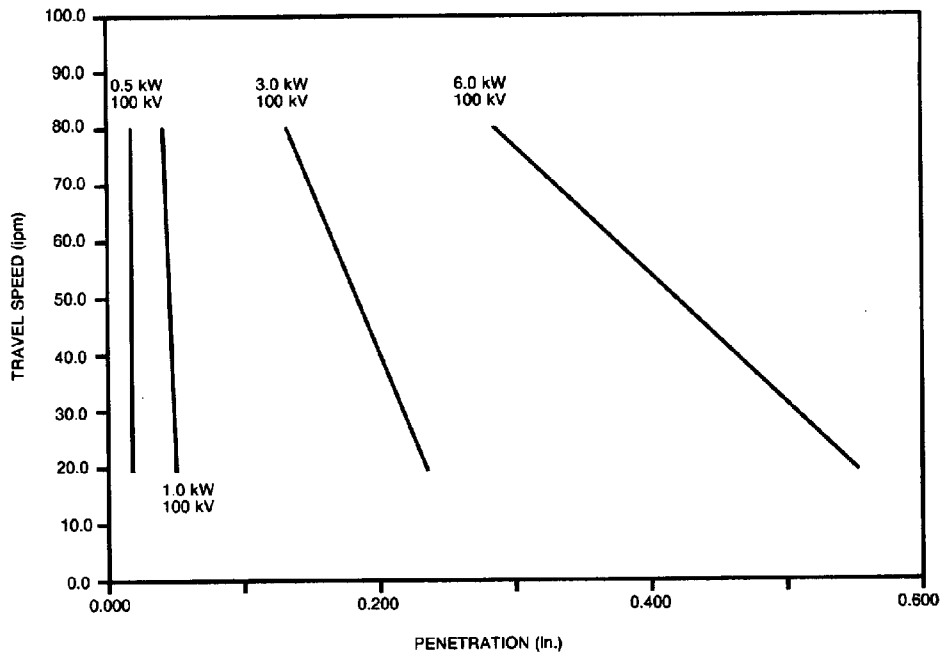


Figure 24 — Power Curves for EBW of Molybdenum Alloys

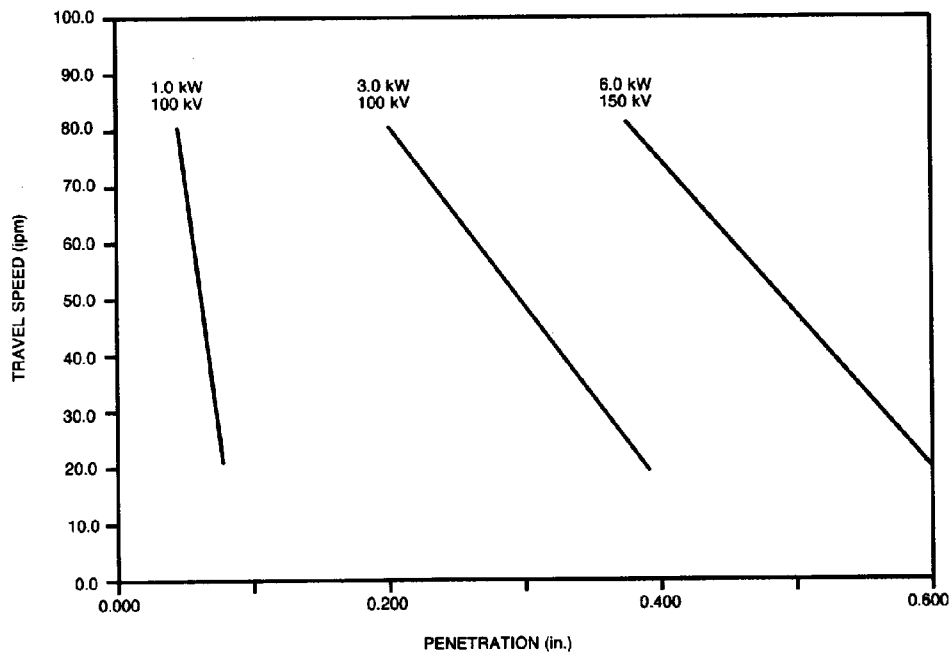


Figure 25 — Power Curves for EBW of Niobium Alloys

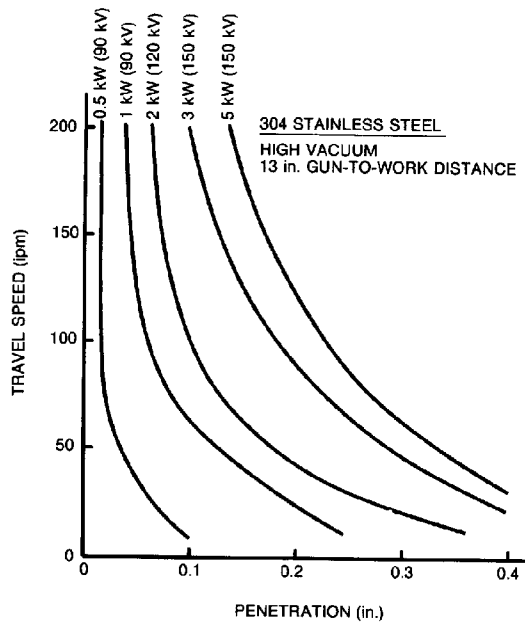


Figure 26 — Power Curves for EBW of Stainless Steel Alloys

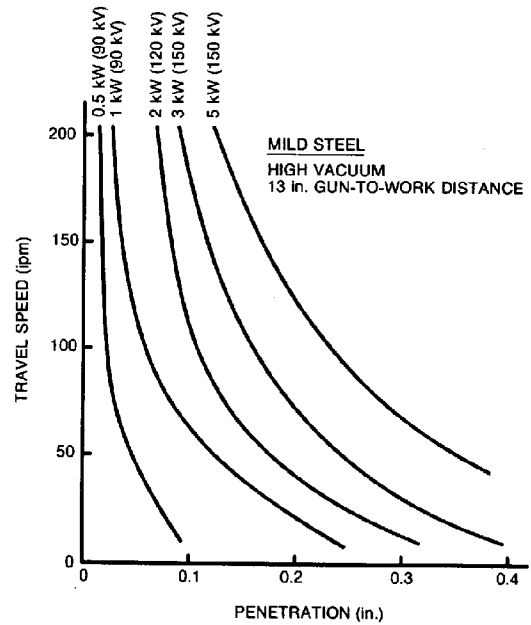


Figure 27 — Power Curves for EBW of Steel Alloys

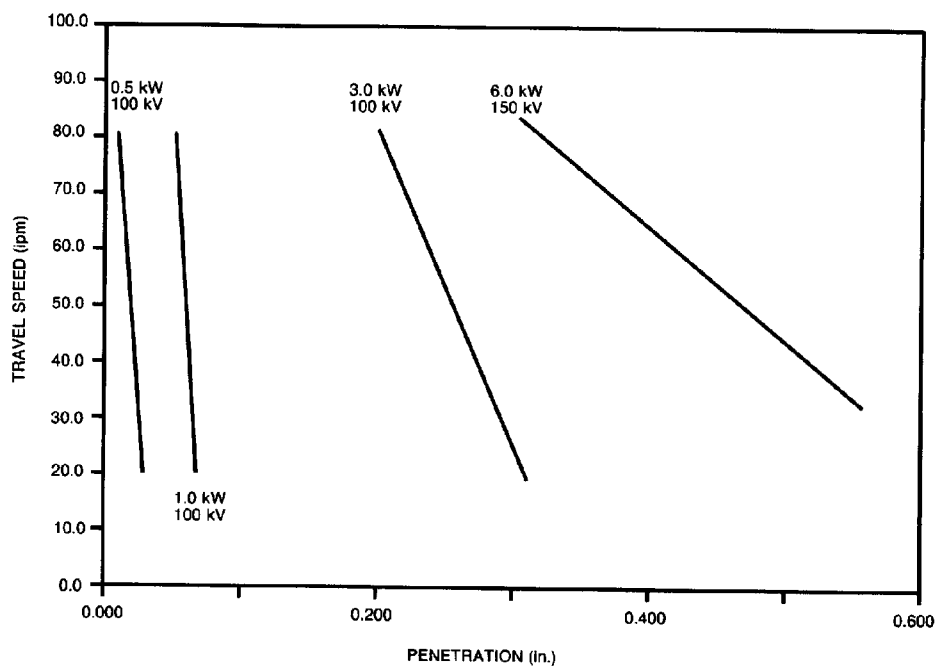
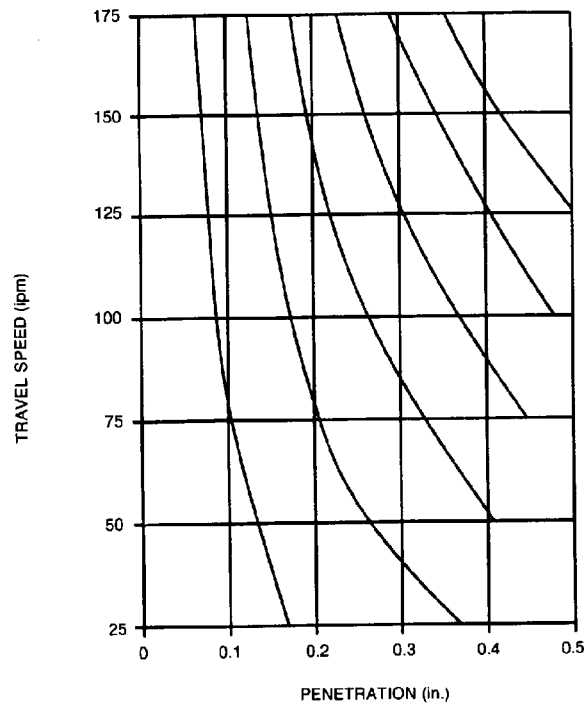


Figure 28 — Power Curves for EBW of Tantalum Alloys



Data taken from a 60 KV system at 10^{-4} torr pressure.

Figure 29 — Power Curves for EBW of Titanium Alloys

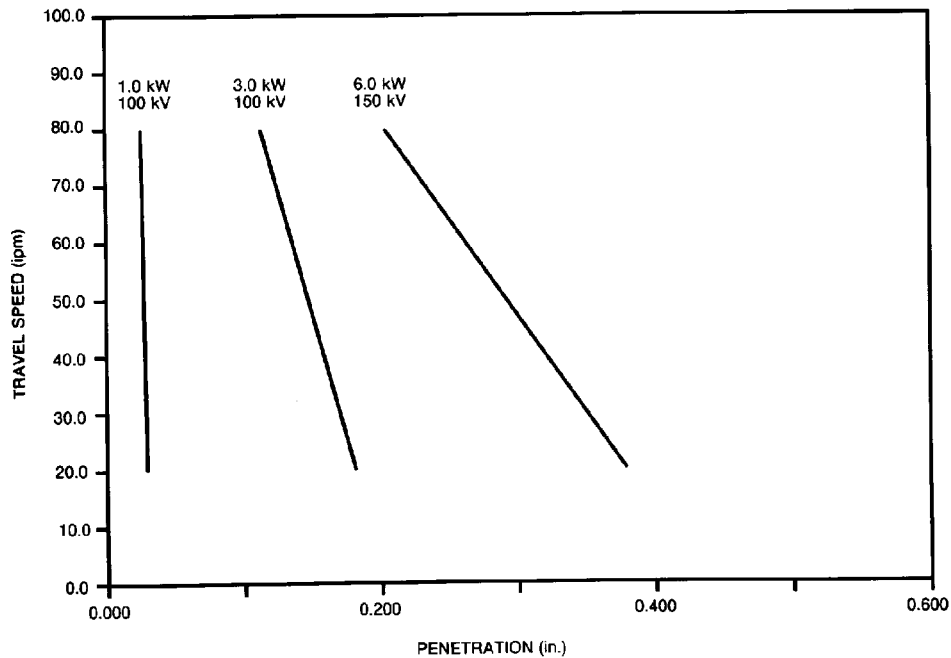


Figure 30 — Power Curves for EBW of Tungsten Alloys

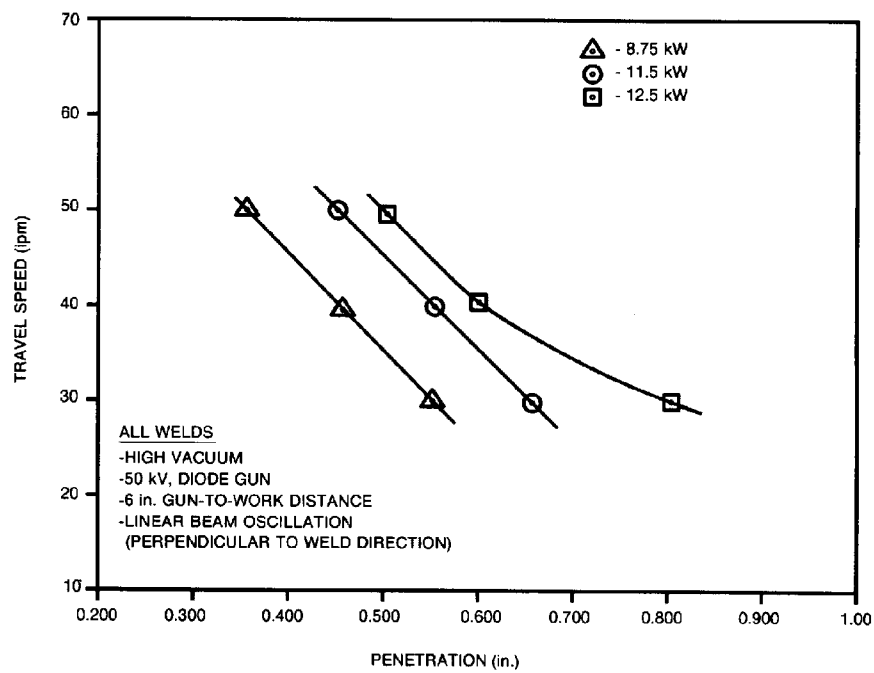


Figure 31 — Power Curves for EB Welding of Zirconium

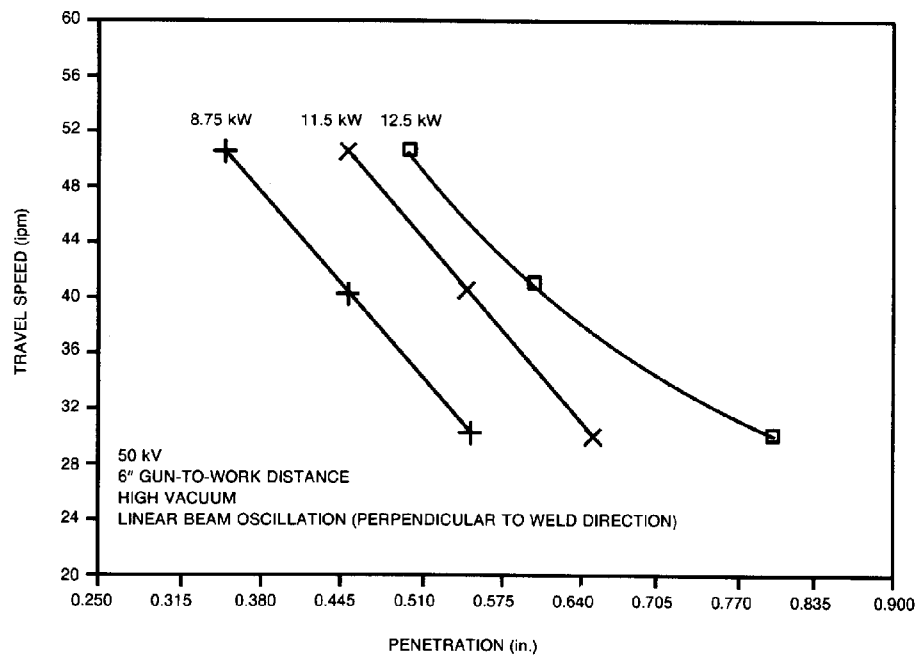


Figure 32 — Power Curves for EBW of Zircoloy

Appendix

Cross Reference Chart for Various Pressure Units

(This Appendix is not a part of ANSI/AWS C7.1-92, *Recommended Practices for Electron Beam Welding*, but is included for information purposes only.)

Conversion of Pressure Units							
mbar	Pa	torr ¹	bar	atm ²	at ³	% vac. ⁴	mm water ⁵
1 013	101 300	760.00	1.01	1.0	1.03	0.0	1.03 x 10 ⁴
1 000	100 000	750.00	1.00	0.987	1.02	1.3	1.02 x 10 ⁴
981	98 100	735.75	0.981	0.968	1.00	3.2	10 ⁴
900	90 000	675.00	0.90	0.888	0.918	11.1	9 177
800	80 000	600.00	0.80	0.789	0.816	21.0	8 157
700	70 000	525.00	0.70	0.691	0.714	30.9	7 137
600	60 000	450.00	0.60	0.592	0.612	40.8	6 118
500	50 000	375.00	0.50	0.494	0.510	50.6	5 098
400	40 000	300.00	0.40	0.395	0.408	60.5	4 078
300	30 000	225.00	0.30	0.296	0.306	70.4	3 059
200	20 000	150.00	0.20	0.197	0.204	80.2	2 039
100	10 000	75.00	0.10	0.099	0.102	90.1	1 019
90	9 000	67.50	0.09	0.089	0.092	91.1	918
80	8 000	60.00	0.08	0.079	0.082	92.1	816
70	7 000	52.50	0.07	0.069	0.071	93.1	714
60	6 000	45.00	0.06	0.059	0.061	94.1	612
50	5 000	37.50	0.05	0.049	0.051	95.1	510
40	4 000	30.00	0.04	0.04	0.041	96.1	408
30	3 000	22.50	0.03	0.03	0.031	97.0	306
20	2 000	15.00	0.02	0.02	0.020	98.0	204
10	1 000	7.50	0.01	0.01	0.010	99.0	102
5	500	3.75	0.005	0.005	0.005	99.5	51
1	100	0.75	0.001	0.001	0.001	99.9	10
0.5	50	0.375	5 x 10 ⁻⁴	5 x 10 ⁻⁴	5 x 10 ⁻⁴	99.9	5
0.1	10	0.075	1 x 10 ⁻⁴	1 x 10 ⁻⁴	1 x 10 ⁻⁴	99.99	1
1 x 10 ⁻²	1	7.5 x 10 ⁻³	1 x 10 ⁻⁵	1 x 10 ⁻⁵	1 x 10 ⁻⁵	99.99	0.1
1 x 10 ⁻ⁿ	1 x 10 ⁻⁽ⁿ⁺²⁾	7.5 x 10 ⁻⁽ⁿ⁺¹⁾	1 x 10 ⁻⁽ⁿ⁺³⁾	1 x 10 ⁻⁽ⁿ⁺³⁾	1 x 10 ⁻⁽ⁿ⁺³⁾		1 x 10 ⁻⁽ⁿ⁻¹⁾
0	0	0	0	0	0	100	0

Notes:

1. 1 torr = 1 mm Hg; 1 micron = 10⁻³ torr (10⁻³ mm Hg)
2. 1 atm (= standard atmosphere) = 101,325 Pa (standard pressure reference)
3. 1 at = 1 techn. atmosphere
4. % vacuum: a pressure increase (or decrease) of approx.
1 mbar corresponds to a change of vacuum of 0.1%
5. 1 mm water (column) = 10⁻⁴ at = 9.8 mbar