AEROSPACE RECOMMENDED PRACTICE

Society of Automotive Engineers, Inc.
400 COMMONWEALTH DRIVE, WARRENDALE, PA. 15096

ARP 1317

Issued 9-15-75
Revised

ELECTRON BEAM WELDING

1. SCOPE:

1.1 This document describes techniques recommended for use in producing electron beam welded joints in materials commonly employed in the aerospace industry.

1.2 The guidelines described herein are oriented towards the use of welding equipment capable of maintaining the workpiece at vacuum levels of 1×10^{-4} torr (133×10^{-4} Pa) or lower during welding.

1.3 Definitions of the terms used herein and specific application of nondestructive testing techniques are contained in ARP 1333, NONDESTRUCTIVE TESTING OF ELECTRON BEAM WELDED JOINTS IN TITANIUM-BASE ALLOYS, available from Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.

1.4 Guidelines and procedures referenced herein regarding radiation levels are contained in U.S. Department of Commerce, Bureau of Standards Handbook No. 60, "X-Ray Protection," available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120, or National Bureau of Standards, Washington, DC 20234.

2. DESCRIPTION OF THE PROCESS:

Electron beam welding is a process wherein coalescence of adjacent metal surfaces is produced by the heat obtained from a concentrated beam composed primarily of high-velocity electrons impinging on the surfaces to be joined. In the type of equipment primarily used in aerospace applications, welding is performed in a vacuum chamber in which both the work piece and the electron gun are at vacuum levels of 1×10^{-4} torr (133×10^{-4} Pa) or lower. Welding power levels are normally in the range of 15 to 150 KV at currents up to 1 ampere.

3. ADVANTAGES OF THE PROCESS:

3.1 Butt joints over 2.0 in. or 50 mm thick can be produced in most weldable materials in a single pass because of the very high energy density available with the process.

3.2 Welds can be produced with a very high depth-to-width ratio with correspondingly narrow heat-affected zones. Shrinkage and distortion are minimized and, with some alloys, metallurgical and mechanical property changes between the parent metal and the weld zone are small when compared with most other fusion welding processes.

3.3 It is often possible to weld joints which would be inaccessible to other fusion welding processes because welds can be made with the workpiece more than 24 in. or 600 mm from the electron gun (depending on gun design and accelerating voltage).

3.4 Different alloys within any one material group (see Section 6) may be welded together; in some cases, alloys from different groups may be welded after experimentation and weld parameter development.

3.5 Metals reactive with the atmosphere can be welded without atmospheric contamination because welding is performed in a vacuum.

4. LIMITATIONS OF THE PROCESS:

4.1 The size of assemblies which can be welded is often limited by the vacuum-chamber size of available equipment. However, in some instances, special chambers can be used which attach to the assembly at the weld joint and avoid the necessity of placing the entire assembly in the chamber.

4.2 Close tolerances are required in detail parts to achieve the degree of accuracy required in fit-up to make an acceptable weld.

4.3 The addition of filler metal is more difficult than with other fusion welding processes.

4.4 The process is not applicable to manual welding.

5. DESIGN CONSIDERATIONS:

5.1 Joints should be located to provide adequate accessibility for the particular type of electron beam gun to be used.

5.2 Joints should be accessible for adequate inspection and nondestructive testing.

5.3 Joints should be located so that the beam does not pass so near other structures as to cause beam deflection. The specific distance at which the beam can be affected will depend on the type of gun being used, the welding parameters, and material or electromagnetic equipment which could cause beam deflection.

5.4 Highly-stressed joints, where possible, should be reinforced (thickened) to reduce stresses in the weld below those in the surrounding structure.

5.5 When possible, joints should be designed so that the weld can be started and stopped on run-off tabs or in an area that will be removed by subsequent machining.

6. MATERIALS: All of the following materials can be joined by electron beam welding each alloy to itself or to other alloys within the same material group. Alloys of different groups may be successfully electron beam welded; however, extensive investigation should be performed before establishing such bi-metal combinations.

Material	Types	Special Requirements
Aluminum and its Alloys	All fusion-weldable alloys, 2014 may be welded with precautions.	Heat treatable alloys except 2219 may require the addition of 4043 or 718 filler metal.
Magnesium and its Alloys	All fusion-weldable alloys	Special techniques may be required to protect the electron gun from metal vapor. Backup strips may be required to minimize undercutting.
Copper and its Alloys	All fusion-weldable alloys. Those alloys containing greater than 2% Pb or 7% Zn may create outgassing problems.	Special techniques may be required to protect the electron gun from metal vapor when Pb- or Zn-containing alloys are welded.

Material	Types	Special Requirements
Carbon and Low-Alloy Steels	Most steels containing up to 0.45% carbon, except free-machining grades. Higher carbon alloys can sometimes be welded with adequate precaution.	The need for preheat and post-weld heat treatment will be determined by the carbon and alloy content of the steel and the material thickness. Preheat will probably be required if the carbon content exceeds 0.30% and the thickness exceeds 0.5 in. or 13 mm.
Corrosion-Restistant Steels	All 200 and 300 series stainless steels and precipitation-hardening steels except free-machining grades. Also 400 series, ferritic and martensitic. 347 CRES may exhibit hot-short cracking.	The need for preheat and post-weld heat treatment will be determined by the carbon content of the steel and the material thickness. Preheat will probably be required if the carbon content exceeds 0.20% and the thickness exceeds 0.5 in. or 13 mm.
Nickel and its Alloys	All fusion-weldable alloys	
Cobalt and its Alloys	All fusion-weldable alloys	
Titanium and its Alloys	All fusion-weldable alloys	
Refractory Metals Ta-Cb Group Tantalum and its alloys Columbium and its alloys	All fusion-weldable alloys	
W-Mo Group Tungsten and its alloys Molybdenum and its alloys		Mechanical properties may limit applications. Preheat is normally required.

7. EQUIPMENT:

7.1 The power supply and focus controls should be capable of producing welding parameters within the tolerances shown:
(a) Voltage ±3 %
(b) Current ±3%
(c) Welding speed ±3%
(d) Focal point at any given gun-to-work distance ±0.125 in. (±3.18 mm).

7.1.1 Some operators have demonstrated excellent repeatability using 0.10% digital meters for voltage and current.

7.2 The vacuum system should be capable of maintaining pressures of 1×10^{-4} torr (133×10^{-4} Pa) or lower. In special circumstances some equipment may be operated at 1×10^{-3} torr (133×10^{-3} Pa). The chamber should be so constructed that, when operating at maximum power, the X-ray radiation level outside the chamber will not exceed the permissible levels of U.S. Department of Commerce, Bureau of Standards Handbook No. 60, "X-Ray Protection."

8. EQUIPMENT AND PROCEDURE CERTIFICATION:

8.1 Prior to initial production welding, a certification weld should be made on a joint representative of the production assembly and at least the following parameters should be recorded on a weld schedule sheet:

(a) Material (alloy and thickness)
(b) Welding speed
(c) Welding voltage
(d) Welding current
(e) Gun-to-work distance
(f) Focus control setting or focal point
(g) Filler metal (when used), alloy, size, and feed rate
(h) Welding position (flat, vertical, horizontal, or other)
(i) Gun angle.

8.2 The certification sample should receive whatever postweld processing is intended for the production weld; i.e., machining, heat treatment, or other fabrication processes.

8.3 The sample should be subjected to whatever nondestructive testing is intended for the production assembly; e.g., X-ray, ultrasonic, penetrant, or magnetic particle, as applicable.

8.4 The sample should be subjected to whatever mechanical tests are required to verify that the weld has the properties required in service. This can usually be condensed to one representative test, either tensile or bend.

8.5 Finally, the sample should be sectioned, examined metallographically, and the minimum width of the weld recorded.

8.6 Recertification should be required if there is a change in any of the following:

(a) Material (parent metal or filler metal)
(b) Joint thickness in excess of ±10%
(c) Welding position
(d) Focus setting exceeding the equivalent of ±0.125 in. (±3.18 mm).
(e) Voltage current or welding speed which will produce a change in heat input of ±5% in kilojoules per inch or 25 mm of weld length.

9. OPERATOR QUALIFICATION:

9.1 Prior to initial production, welding operators should set up and weld a test plate representative of production joints. The welding parameters should be from an established weld schedule. The test weld should be processed and tested in the same way as the procedure certification specimen.

9.2 Successful completion of welding, post-weld processing, and inspection of the test plate should be considered qualification for all materials in all thicknesses for which weld schedules have been certified. If the weld schedule used had not been previously certified, successful completion of the test should qualify the operator and certify the schedule.

9.3 Requalification in the same manner as in 9.1 should be required if the operator has not made a production weld for a six-month period or fails to maintain a record of good workmanship in production welding.

10. THE WELDING PROCESS:

10.1 Tooling and Fit-Up:

10.1.1 All tooling within 6.0 in. or 150 mm of the weld joint should be made from nonmagnetic materials or be degaussed to acceptable limits. Electromagnetic devices should be shielded if such devices could affect the electron beam.

10.1.2 Tooling should provide positive lateral pressure to prevent the joint from opening.

10.1.3 A tacking pass may be used to aid the tool in holding the joint together except when welding materials where a brittle tack weld could result; e.g., SAE 4340 steel.

10.1.4 Joints should be as close fitting as possible. For most applications the gap should not exceed 0.010 in. (0.25 mm) or 10% of the joint thickness, whichever is less. For joint thicknesses of 0.25 in. (6.4 mm) and less a smaller allowable gap may be necessary. In ring - or plug-type joints an interference fit of 0.001 - 0.003 in. (0.03 - 0.08 mm) is recommended. Surface finish of faying surfaces should be 125 microin. (3.18 μm), or better.

10.1.5 Mismatch should not exceed 0.030 in. (0.76 mm) or 10% of the joint thickness, whichever is less.

10.1.6 Magnetic materials should be degaussed prior to welding.

10.1.7 Parts of the fixture subject to impingement by the electron beam should be made of the same material as that being welded.

10.2 Cleaning of Parts to Be Welded: All surfaces to be welded should be clean and free from foreign material and contaminants. Cleaning should be performed immediately prior to welding wherever possible.

10.2.1 Aluminum and magnesium alloys should be chemically or mechanically cleaned in the area of the joint. Welding should be completed as soon as practicable after cleaning.

10.2.2 Titanium alloys should be cleaned with aqueous alkaline solutions or nonhalogenated solvents. For welding thicknesses less than 0.50 in. or 13 mm, acid etching to remove not less than 0.0002 in. or 0.005 mm per surface is recommended. Welding should take place as soon as practicable after etching.

10.2.3 For most other metals, alkaline or solvent cleaning is usually sufficient.

10.3 Welding Parameters:

10.3.1 Power: It is usually possible to produce quality welds with a variety of combinations of voltage and current; however, with electron guns operating in the medium voltage range (up to 60 KV), it is recommended that voltage be kept on the low side and higher amperage used.

10.3.2 Welding Speed: Quality welds in thinner materials can be made at speeds well over 100 in. or 2.5 m per min.; however, for thicknesses of 0.50 - 2.0 in. or 13 - 50 mm, the best results, from both weld bead contour and metallurgical aspects, are usually obtained in the 20 - 65 in. or 0.5 - 1.6 m per min. range.

10.3.3 Focal Point: Best results are usually achieved with the focal point at the face surface of the joint, or slightly above or below the surface. In thicknesses approaching 2.0 in. or 50 mm or more, best results are sometimes achieved with the focus set to approximately mid-thickness.

10.3.4 Gun-to-Work Distance:

10.3.4.1 For electron guns operating at medium voltage (up to 60 KV), a 6 - 10 in. or 150 - 250 mm gun-to-work distance is recommended for providing good beam control and also clearance for tooling and filler wire feed mechanisms. Gun-to-work distances exceeding 24 in. or 600 mm should be avoided.

10.3.4.2 Electron guns capable of operating up to 150 KV have a wider range of usable gun-to-work distance and successful welds can be produced at over 36 in. or 900 mm.

10.3.5 Weld Parameter Combinations: In most cases, several combinations of speed, voltage, amperage, and beam focus will produce serviceable welds; however, the parameters selected should meet the following two requirements for butt welds in thicknesses over 0.25 in. or 6.4 mm:

(a) The cross section of the weld should have parallel sides or a slight "V" shape; however, a slight hour-glass shape may be unavoidable in joints over 1 in. or 50 mm thick. Barrel-shaped welds should be avoided by adjustment of the beam focal point.

(b) Weld width should be consistent with the material, joint thickness, and design application. For joints over 0.025 in. (0.64 mm) thick, weld width of 0.060 in. or 1.52 mm or more is advisable to minimize the possibility of missed joints.

10.4 Filler Metal: When required, filler metal can be added to the weld either as preplaced wire resistance tackwelded in place, as shims between the faying surfaces, or with a mechanical feeder. The position of the wire guide tip is critical because of the relatively small diameter of the electron beam as compared with a tungsten arc.

10.4.1 Filler metal composition, in almost all cases, should be the same as would be used for gas-tungsten-arc welding for the particular parent material or materials.

10.4.2 When filler wire is added for metallurgical purposes, the effective depth of dilution with filler metal is approximately 0.25 in. or 6.4 mm. The only way to achieve full depth dilution in thicker joints is with shims between the faying surfaces and the characteristic narrow width of the weld limits the effectiveness of this approach.

10.5 Preheat and Postheat: Heating of the material may sometimes be accomplished with a defocussed electron beam.

10.6 Back-up Material: Back-up material of the same alloy being welded may be used to prevent excessive drop-thru.

11. POST WELD PROCESSING:

11.1 Machining: Machining of both the face and root surfaces of welds is advantageous to provide:

(a) Substantial increase in fatigue life.

(b) Improved capability for nondestructive testing such as ultrasonic, radiographic, dye penetrant, fluorescent penetrant, and magnetic particle inspection.

11.2 Heat Treatment:

11.2.1 Many alloys can be welded in the heat treated (hardened) condition to produce joints which approach parent-metal tensile properties with no post-weld heat treatment. Aluminum alloys are an example of this approach (i.e., 2014-T651, 80% and 2219-T87, 75% ultimate tensile strength joint efficiency); however, post-weld aging may further improve properties.

11.2.2 Other alloys can produce 100% joint efficiencies in heat treated material if merely given a post-weld aging, retemper, or stress-relief, as applicable. Titanium alloys are a good example (i.e., Titanium 6A1-4V, Condition STA, 100% ultimate tensile strength joint efficiency).

11.2.3 Some alloys, such as high-strength, low-alloy steels, require full post-weld heat treatment to achieve high joint efficiencies or to maintain other desired properties such as corrosion resistance, ductility, or fracture toughness.

11.2.4 With alloys not hardenable by heat treatment or alloys used in the annealed condition, post-weld stress-relief may improve fatigue properties, particularly if stress-loading in service is parallel to the joint.

11.3 Finishing:

11.3.1 Most finishes commonly applied to a particular alloy can also be applied to electron beam welds.

11.3.2 Care should be exercised with chemical finishing processes such as anodizing or pickling, as the welds may be susceptible to intergranular attack if the chemical composition of the bath is not properly controlled.

12. PROCESS CONTROL:

12.1 The certified welding schedule should be posted near the welding machine control panel at all times when welding is in progress.

12.2 The machine settings should be verified by a second person, either forcman, inspector, or welding engineer, as applicable.

12.3 It is recommended that the format of the weld schedule sheet be essentially a simplified drawing of the control panel.

12.4 When a machine is first put in operation, bead-on-plate test welds should be made daily, sectioned, and examined to verify that parameters are reproducible. As experience is gained, the interval between verification welds can be extended considerably. Verification welds should be made, however, after any major maintenance or repair operations are performed on the machine.

12.5 Prior to welding a joint, it is advisable to verify the alignment of the beam with the joint, either by visual test welds or by a beam scanning apparatus.

13. INSPECTION AND QUALITY CONTROL:

13.1 Applicability of Nondestructive Test Methods: The extent to which any or all of the nondestructive test methods discussed below are applied will depend on the geometry of the part and its intended application. There are many instances where any one of the inspection methods will assure the required quality; however, highly-stressed joints in thick sections may require use of all four methods.

13.1.1 Witness Lines: Prior to welding, "witness lines" or "reference lines" should be scribed on both sides of the joint, on both the face and root sides of the pieces to be welded. Excellent accuracy can be obtained by using 5 lines on either side of the joint spaced 0.03 in. or 0.8 mm apart.

13.1.1.1 After welding, the number of spaces between lines remaining unmelted should be counted to determine the location of the weld center-line with respect to the joint. Knowing the minimum weld width from the certification test plates as determined in 8.5, it can be verified that both sides of the joint have been fused.

13.1.1.2 The use of witness lines is explained in more detail in ARP 1333.

13.1.2 Ultrasonic Inspection: Ultrasonic inspection can be used as a supplement to, or as an alternate for, witness line inspection to detect an unfused joint. It can also be used to detect the presence of and to determine the depth of, sub-surface discontinuities. The approximate size of discontinuities can be determined; however, the size is more accurately determined by radiographic inspection. Ultrasonic inspection is most useful in examining joints more than 1 in. or 25 mm in thickness because its sensitivity does not decrease appreciably as thickness increases.

13.1.3 Radiographic Inspection: Radiographic inspection should be used to detect the presence of, and to determine the size of, sub-surface discontinuities. It may also be used to locate accurately discontinuities that can be repaired by rewelding the joint.

13.1.4 Dye Penetrant, Fluorescent Penetrant, or Magnetic Particle Inspection: Dye penetrant, fluorescent penetrant, or magnetic particle inspection should be used to detect small surface flaws which may be missed by ultrasonic or radiographic inspection.

13.2 Acceptance Criteria:

13.2.1 Undercut and Underfill: The cumulative effects of undercut and underfill should not exceed the post-weld machining allowances permitted by drawing dimensions. The allowable underfill should be specified on the drawing for surfaces which are not machined after welding.

13.2.2 Penetration:

13.2.2.1 Structural Joints: Joint penetration should be 100%; however, on special designs this may be achieved by post-weld machining.

13.2.2.2 Nonstructural Joints: Joint penetration may be less than 100%, when specified on the drawing.

13.2.3 Incomplete Fusion: Incomplete fusion or missed joints should not be permitted.

13.2.4 Color: Discoloration on the part due to metal vapor deposition is acceptable.

13.2.5 Cracks: There should be no surface or internal cracks.

13.2.6 Porosity and Voids:

(a) Internal porosity and cavities should be determined radiographically and each discontinuity should be size-classified by its largest dimension.

(b) Interconnected porosity should be considered as one single pore for size-classification purposes.

(c) Porosity, regardless of shape, having sharp terminations, edges, tails, or crack-like appearance should not be acceptable.

(d) Pores or voids open to the surface should be acceptable, provided they do not exceed 1/2 the limits set forth in 13.2.7.

(e) Porosity in a weld joint of cast-to-cast or cast-to-wrought material should be permissible within the limits of the porosity acceptance criteria for the casting.

13.2.7 Suggested Limits of Porosity and Shrinkage Voids: When sufficient information is available, the maximum size, number, and location of internal discontinuities should be determined on a fracture-toughness basis for a particular weld, and the acceptance criteria shown on the drawing. If this cannot be done, acceptance criteria developed for other fusion welding processes may apply for most materials or the guidelines shown below and in Table I may be used for structural welds.

13.2.7.1 Individual Internal Discontinuities: Maximum pore diameter should not exceed the value specified in Table I. Two or more adjacent discontinuities, other than aligned (See 13.2.7.3), should be treated as one discontinuity (excluding the space between) when the spacing between them is less than three times the greatest dimension of the smaller adjacent discontinuity.

13.2.7.2 Total Internal Discontinuities: The sum of the areas of all cavities within any 1.0-in. (25.4-mm) length of weld should not exceed the value specified in Table I, or that found by interpolation using the factor 0.025T sq in. or 0.0125 sq in. (0.635T mm^2 or 8.06 mm^2), whichever is less.

13.2.7.3 Aligned Internal Discontinuities: For any group of five or more individual discontinuities within any 1.0-in. (25-mm) length of weld whose images are intersected by a straight line (regardless of orientation within the weld) and where the distance between adjacent discontinuities of the group being considered is less than four times the longest dimension of the smallest adjacent discontinuity, the allowable limits should not exceed the value specified in Table I, or that found by interpolation using the factor 0.010T sq in. or 0.0063 sq in. (0.254T mm^2 or 4.06 mm^2), whichever is less.

14. REPAIR OF DEFECTS:

14.1 The most common method of repairing defects in electron beam welds is to reweld the joint, either locally or full length. In some instances, such as joints over 1 in. or 25 mm thick, it may be desirable to use filler metal when rewelding in order to minimize undercutting.

14.2 In order to repair a defect by rewelding, the defect must be accurately located, preferably by radiographic techniques, to enable the electron beam to be aligned precisely on the defect.

14.3 The number of times a joint can be rewelded without causing undesirable metallurgical effects will depend on the material. Some alloys, such as Titanium 6A1-4V, can be rewelded as many as six times with no detrimental effects.

14.4 Localized defects in thin joints or defects near the surface of thicker joints can sometimes be repaired by other fusion welding processes, such as gas-tungsten-arc or plasma-arc welding.

15. SAFETY:

15.1 If the vacuum chamber is large enough for a person to enter it, the door control should be activated only by a key switch and the key made available only to the welding operator. The door should be equipped with a bell or other alarm which will sound if the door is being closed and should be equipped with an easily-activated opening device on the inside of the door.

15.2 The high voltage should have safety interlocks to prevent it from being activated:

(a) if the chamber door is open

(b) if the connectors in the high voltage cables are improperly coupled

(c) if the chamber is not under at least partial vacuum

15.3 The chamber should be so constructed that radiation levels of U.S. Department of Commerce, Bureau of Standards Handbook No. 60, "X-Ray Protection," are not exceeded.