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ELECTRON BEAM WELDING
OF NUCLEAR FUEL CLADDING COMPONENTS

By

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ABSTRACT

The rapid technological development of the nuclear and space industries has placed a great demand on metal joining processes. One of the most promising processes is electron beam welding. Welding with the electron beam offers high integrity in addition to the ability to fabricate unusual configurations. Advanced nuclear fuels require both reliability and unusual designs for satisfactory operation under extreme conditions of temperature and stress. To investigate the problems and techniques involved in fabricating large, advanced nuclear fuel components from Zircaloy-2 material, several cladding pieces were designed and built using the electron beam process. These designs included five basic joint types for assembling the cladding. Destructive and nondestructive examinations were employed including corrosion testing and extensive metallographic examination.

Weldment size, "fit-up" of the parts to be joined, fixturing and work carriage mechanisms, as they pertain to electron beam welding, are also discussed.

The electron beam process has been demonstrated as a very satisfactory method for fabricating unusual fuel cladding. Fuel cladding components with lengths up to 8 ft have been fabricated for in-reactor irradiation.

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ELECTRON BEAM WELDING OF NUCLEAR FUEL CLADDING COMPONENTS

INTRODUCTION

The continual development of nuclear and space-age metals and alloys has created a demand for improved welding technology. Some of the most promising heat and corrosion resistant materials are those that are the most difficult to refine, shape, and join. These materials include the reactive and refractory materials and their alloys--e. g. , tungsten, molybdenum, tantalum, niobium, hafnium, titanium, beryllium, and zirconium. The relatively new process of electron beam welding has provided industry with the ability to fabricate these materials into a wide variety of structural components. The use of this process is not limited to hard-to-join materials. Electron beam welding provides a means of obtaining large depth-to-width ratios, high energy concentration in a small area, and extremely narrow heat affected zones. These advantages are not available in the more conventional processes.

While the idea of localized heating by bombardment of electrons is not new, the development of sophisticated equipment has occurred only within the last few years. This welding process derives its unique effect from a beam of electrons emitted from a cathode, usually made from tungsten. The beam is accelerated to a high velocity through a high potential and accurately focused by magnetic coils to produce a spot with an extremely high energy density.

A vacuum chamber and suitable pumping equipment to provide a vacuum of approximately 1 torr are necessary for satisfactory operation of the electron beam. At a higher pressure, gas molecules would diffuse the electrons emitted from the cathode, so that a fine beam focus could not be obtained.

Electron beam welding has been extended beyond the laboratory curiosity and experimental tool stage to a very successful production tool. Its major use, until recently, has been in the fabrication of relatively small parts. Today the use of the equipment is extending to larger and larger pieces as evidenced by the growing size of welding chambers.

DISCUSSION

The low cost fabrication of nuclear fuel elements that will operate with high heat generation rates and complete safety is the ultimate objective of fuel element manufacturers. To this end, several unique fuel element cladding configurations were fabricated by electron beam welding to demonstrate the flexibility of the process and the feasibility of welding large, unusual shapes that cannot be readily fabricated by other methods. Sections of each piece of cladding were thoroughly examined by destructive and nondestructive techniques to determine depth of penetration, extent of heat-affected zone, and the amount of porosity.⁽¹⁾

Five basic electron beam welding joint designs were incorporated in four different cladding configurations. These joint designs are summarized in Figure 1. Arrows indicate direction of the electron beam and point to the area of beam impingement.

(1) The preparation of the parts for welding and the evaluation of the welded components were performed at Hanford. The components were welded by an offsite contractor.

Joint Type
Designation

Type of Weld

1

Burn-Through

2

Tangential

3

Burn-Through

4

Tangential

5

Tangential

FIGURE 1

Weld Joint Descriptions and Designations

Cladding dimensions are shown in Table I.

TABLE I
FUEL CLADDING DIMENSIONS

<u>Joint Type</u>	<u>Part</u>	<u>Dimensions</u>
1	Tubular Cladding	3.070 in. OD x 0.060 in. wall
	Rib	0.062 in. thick
2	Tubular Cladding	2.330 in. OD x 0.060 in. wall
	Rib	0.062 in. thick
3	Large Tubular Cladding	2.330 in. OD x 0.060 in. wall
	Small Tubular Cladding	0.565 in. OD x 0.30 in. wall
4	Both Pieces of Tubular Cladding	0.565 in. OD x 0.030 in. wall
5	Tubular Cladding	0.565 in. OD x 0.030 in. wall
	Round Wire	0.072 in. diameter

Although electron beam welding offers the research worker and fabricator a method of making many unusual welds in addition to conventional joints, there are special considerations that must be taken into account. These considerations are not of serious importance when more conventional welding methods are employed.

Size of Weldment

Size and complexity of the equipment are increased when the physical size of the weldment is increased. A longitudinal weld on a 1 ft long section is relatively easy to make, but an 8 ft section can be considerably more difficult. When spacer ribs were welded to the outside of a 1 ft long tube, distortion of the ribs was negligible. Little trouble from rib distortion or tube bow was encountered when this ribbed tube was inserted into a tube which had an ID the same dimension as the OD of the ribs, and "blind" burn-through welds were made through the outer tube into the ribs (Figure 2). Distortion of ribs (and tube), when welded to an 8 ft long tube, would

not be negligible without elaborate fixturing to restrain the rib and tube. The burn-through weld is considerably more difficult to make on the 8 ft long section than on the 1 ft long section because the distorted rib cannot be seen through the outer tube. Also, since tube bow varies with length, good fit-up and the burn-through weld would be difficult to achieve.

Cost of weldment, then, increases with length. Fixturing is necessarily more elaborate and more care is required to assure quality work.

Fit-Up

The fit-up of the pieces to be joined is important when conventional welding processes are used, but the importance is vastly increased with electron beam welding. This is due to the extremely small diameter beam impingement area. Welding longitudinal ribs to tubes is an example. There is essentially a point contact between the rib and the tube. If there is a gap between the rib and tube of as little as 0.015 in. at one point, no weld may occur at that point or, at best, a thinning of the weld metal near the tube will take place.

Another example of necessity of good fit-up is vividly illustrated in Figures 3 and 4. The cross-section of this weldment is the same as Figure 2. Figure 3 shows the results of a gap between the rib and the

FIGURE 2
Tube-in-Tube Cross Section

FIGURE 3
Weld with Poor Fit-up of Parts

FIGURE 4
Weld with Good Part Fit-up

inside of the outer tube. Figure 4 indicates the results obtained from a good fit-up of the same type of joint.

Fixturing

Fixturing plays an important part in obtaining quality welds on large, long or intricately shaped pieces. For research and development work, effective fixturing can be kept simple; however, production of a large number of long pieces may change the fixturing picture. Drive mechanisms may be introduced to rotate the part into a new position after each weld, automatic clamping devices may be required that can release parts and reclamp after positioning the pieces, storage and feeding mechanisms may be needed to supply parts, and all must be done in such a manner that the final product is a precise fabrication. Cost of elaborate fixturing may be high, and with each addition to the fixture an accompanying increase in the size of the vacuum chamber must be considered.

Work Carriages

Smooth operation and essentially vibration-free movement are necessary features of work carriages. Vibration control is one key to quality work. Where pinpoint accuracy in placement of the small diameter electron beam on the joint is necessary, any vibration which has a component horizontal to the direction of travel can be detrimental to the weld. Vibration in this direction will widen the weld unnecessarily and in some instances result in burning through thin cladding. It will also greatly hamper the operator's control over the welding.

Accurate carriage travel is particularly important on long weldments. Carriage travel should not deviate more than 0.005 in. from a straight path. Furthermore, the importance of accurate carriage travel increases as the wall thickness of the tube decreases. Accurate carriage travel will require fewer operator adjustments and assure high quality welds.

WELDING RESULTS

All welding was performed on reactor grade Zircaloy-2 material.

Type 1 Weldments

Type 1 joints are burn-through welds in which the electron beam impinges radially on the surface of the outer tube. The beam completely penetrates the cladding and continues on into the rib material.

Figures 5A and 5B clearly show the result of a poor fit-up between rib and tube in this type of joint. The appearance of the outside of the tube when this condition exists is illustrated in Figure 3. Figure 5 shows that the area of the weld metal used to partially fill the void between the ID of the tube and the top of the rib is far greater than the area of the indentation at the top of the weld. The metal to fill the void must not have come from the tube material directly above the void. It must have come from the joint material on either side of the metal shown in the plane of this cross section. The porosity in this joint type will be discussed later along with porosity found in all of the four remaining joints.

The bulge of metal in Figure 6 is typical for this type of joint when the fit-up is good and the welding beam penetrates close to one side of the rib. There is essentially two-point contact between the rib and the tube, i.e., since the tube is curved, only the two edges of the rib will touch it. As the beam penetrates the tube, the rib edge close to the beam heats, melts, and the molten edge sags to form the bulge.

A good weld is illustrated in Figure 7. There is good fit-up and the weld is only slightly off-center.

A Type 1 weld is considered perfect if the welding beam penetrates the exact center of the rib and the weld is wide enough to eliminate the slight crevices between the rib and the tube on either side of the weld metal as in Figure 7.

Polarized Light

5A

32X

Bright Field

5B

32X

FIGURE 5

Poor Fit-up on Type 1 Weld

Polarized Light

FIGURE 6

32X

Type 1 Weld with Electron Beam Penetration to one Side of Rib

Polarized Light

FIGURE 7

32X

An Acceptable Type 1 Weld

Type 2 Weldments

This is a joint fabricated by aiming the beam tangentially to the cylindrical cladding and toward the point of contact between the rib and tube. One weld pass is made on each side of the rib to assure complete penetration and to eliminate the rough surface that would occur on the root side of the weld if single-pass full penetration were employed.

Figures 8, 9A, and 9B show a typical joint section. Figure 8 indicates that the electron beam has a tendency to curve in this particular type of joint. The welds from both sides of the rib curve toward the top of the rib. The mechanism of this phenomenon is not known; however, the shape of the part apparently affects the electron beam.

A welded joint with incomplete penetration of the electron beam on both sides of the rib is shown in Figure 10.

Figures 9A and 9B illustrate the type of weld quality acceptable for nuclear fuel elements. The heat affected zone is narrow and there is complete penetration. Undercutting of the rib is slight with a smooth contour, and there is no porosity in this section. Porosity is occasionally encountered with this joint as shown in Figure 11.

Type 3 Weldments

This is a joint comprised of a burn-through weld between two tubes with a small tube in contact with the ID of a large tube. The electron beam initially impinges on the large tube and penetrates into the smaller tube to form the weld.

A normal weld of this joint type is illustrated in Figures 12A and 12B. The electron beam appears to have initially impinged on a point of the large tube that was directly above the point of contact of the two tubes. The fit between the tubes was good and the beam did not penetrate to the inside of the small tube.

Bright Field

FIGURE 8
A Good Type 2 Weld

50X

Polarized Light

9A

32X

Bright Field

9B

32X

FIGURE 9

A Good Type 2 Weld

Bright Field

FIGURE 10

44X

Incomplete Penetration on a Type 2 Weld

Bright Field

FIGURE 11

32X

Porosity in a Type 2 Weld

Polarized Light

12A

32X

Bright Field

12B

32X

FIGURE 12

A Good Type 3 Weld

Figures 13A and 13B show the results of excessive penetration and poor fit. Excessive penetration results in irregular protrusions on the inside of the small tube which are difficult to remove but do not affect the integrity of the weld.

A close fit between the two tubes may or may not be desirable, depending on the ultimate use of the assembly. The photomicrograph shows a gap between tubes of approximately 0.01 inches. A successful weld may be made with a much greater gap, but the optimum gap width is dependent on the width of the weld and the size of the groove at the top of the weld that can be tolerated.

An interesting distribution of porosity is apparent in Figure 13A and will be discussed later.

Type 4 Weldments

Two small tubes, laid side by side, can be joined using either one pass or a pass on each side of the joint. Since the metal to fill the joint comes from the walls of the tubes, a close fit between the pieces is essential to prevent wall thinning. With greater spacing, more metal will have to be taken from the walls to fill the joint. This situation will result in a reduced tube wall thickness.

Figure 14 is an illustration of a typical two-pass weldment of this type.

Figures 15 and 16 show the one-pass joint. Figure 15 is an acceptable weld, while the joint in Figure 16 has insufficient penetration.

Figures 17 and 18 show porosity in the two-pass and one-pass welds, respectively.

Type 5 Weldments

This round wire-to-tube joint is extremely difficult to achieve. The point of beam impingement and the path of beam penetration have to be carefully selected in order to minimize melting of the wire and

Polzrized Light

13A

32X

Bright Field

13B

32X

FIGURE 13

Excessive Penetration and Poor Fit on Type 3 Welds

Polarized Light

FIGURE 14

32X

A Good Two-Pass Type 4 Weld

Bright Field

FIGURE 15

32X

A Good One-Pass Type 4 Weld

Polarized Light

FIGURE 16

32X

One-Pass Type 4 Weld Showing Insufficient Penetration

Polarized Light

FIGURE 17

32X

Two-Pass Type 4 Weld Showing Porosity

Polarized Light

FIGURE 18

36X

One-Pass Type 4 Weld Showing Porosity

tube. In addition, extreme caution is required to prevent undercutting of the tube. Figures 19A and 19B are cross sections of a weld. Because of point contact between the wire and tube, metal to fill the joint must be obtained from either the wire or the tube. In most cases, the metal should be taken from the wire to eliminate tube wall thinning. If an assembly is to be made from a group containing joints of this type, dimensional changes should be anticipated.

Polarized Light

19A

32X

Bright Field

19B

32X

FIGURE 19
Type 5 Weld

Figure 20 is a photomicrograph of a longitudinal section of Type 1 and 2 joints. Joint 1 is at the top of the photograph and joint 2 at the bottom. Note the grain structure in the Type 2 joint. The direction of travel of the welding beam is clearly discernible. The apparent line near the bottom of the photo, in the Type 2 joint, indicates the center of the melt with the electron beam coming from a direction perpendicular to the plane of the paper and traveling from right to left. Figure 21 is an enlarged portion of this section.

Figure 22 and Figure 23 are longitudinal photomicrographs of joints 3 and 4, respectively.

Weld Joint Porosity

Very little mention of porosity has been made in the preceding paragraphs. This is because the porosity in all joints has much in common. The small porosity, with but few exceptions, occurred along the edges of the melts. The large holes which were found only in Type 4 weldments always appeared near the point of maximum beam penetration.

Porosity is attributed to impurities in the materials used and not to the electron beam welding process.

Welding Parameters

Table II lists the parameters for the electron beam welding of the various weld types.

TABLE II

WELDING PARAMETERS

Weld Type	Accelerating Potential (kv)	Electron Beam Current (ma)	Speed of Travel (in. /min)
1	100	6	50
2	100	3	30
3	100	4.5	30
4	90	3	30
5	80	2.5	30

FIGURE 20

11X

Longitudinal Section of Type 1 and Type 2 Joints

FIGURE 21

43X

Enlargement of the Apparent Line
Shown in the Lower Part of Figure 20

FIGURE 22

11X

Longitudinal Section of Type 3 Joint

FIGURE 23

11X

Longitudinal Section of Type 4 Joint

CONCLUSIONS

The electron beam welding process has proven highly successful for fabricating fuel element claddings having either standard or unusual configurations. The success of initial trials prompted the fabrication of actual pieces of cladding, using the full 9 ft long tubes. Photographs of these pieces may be seen in Figure 24, which shows a preassembled 19-rod cluster and a tube-in-tube cladding assembly, and Figure 25, which shows spacer ribs attached to the nested tubular cladding parts.

Figures 26 and 27 are additional experimental configurations that illustrate versatility of the electron beam welding process.

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FIGURE 24

Pre-Assembled 19-Rod Cluster
and Tube-in-Tube Fuel Element Cladding Assemblies

AEC-GE RICHLAND, WASH.

FIGURE 25
Nested Tubular Cladding Parts

FIGURE 26

Arch-Supported Fuel Element Cladding

FIGURE 27

Inverted Cluster Fuel Element Cladding

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