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DEVELOPMENT OF AUTOMATED WELDING PROCESSES FOR FIELD
FABRICATION OF THICK-WALLED PRESSURE VESSELS—ELECTRON
BEAM METHOD

Second Quarterly Report, January 1—March 31, 1978

By
Charles M. Weber

Work Performed Under Contract No. EF-77-C-01-2606

The Babcock & Wilcox Company
Research & Development Division
Alliance, Ohio

MASTER

U. S. DEPARTMENT OF ENERGY

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DEVELOPMENT OF AUTOMATED WELDING PROCESSES FOR
FIELD FABRICATION OF THICK-WALLED PRESSURE
VESSELS — ELECTRON BEAM METHOD

Second Quarterly Report for the
Period 1 January 1978 — 31 March 1978

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Under Contract EF-77-C-01-2606

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ABSTRACT

This report is the second quarterly report of a project to develop and demonstrate an electron beam welding procedure for welding 8" thick SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) steel. It covers the progress made during the period January-March 1978. The steel ordered for use in the project has not yet been received, which has resulted in a delay of the scheduled work.

A procedure for eliminating unwanted displacements of the electron beam and the electron beam weld arising from magnetic fields was developed. A magnetic shield was designed, fabricated, and shown to be effective at protecting the electron beam from magnetic fields between the steel plate and the electron gun. Magnetic fields existing within the steel plate were shown to be of no concern.

1.0 OBJECTIVE & SCOPE OF WORK

1.1 OBJECTIVE

The objective of this project is to develop and demonstrate an electron beam welding procedure for welding 8" thick SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) material, in both the horizontal and vertical positions, acceptable to the ASME Boiler and Pressure Vessel Code Section VIII, Division 2.

In addition to the work necessary to accomplish the objective, work will be performed to acquire information relative to the feasibility of electron beam welding coal gasification units.

1.2 SCOPE OF WORK

The following summarizes the planned work:

Step 1 — Planning

This step identifies the planning function necessary for executing this contract. The plans include the budget, resources, schedule, work description, etc., in preparation for performance of the work.

Step 2 — Material Procurement

This step identifies the procurement of a sufficient quantity of SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) to be used in the project.

Step 3 — Partial Penetration Procedure Development

The objective of this step is to develop electron beam welding procedures for making partial penetration welds (~4-1/2" deep) at three vacuum levels (~0.06, 40, and 100 microns) in both the horizontal and vertical positions.

Step 4 — Selection of Vacuum Level

From the results obtained in Step 3, a welding procedure, for each position, will be selected that gives the most consistent and reliable results at the highest pressure.

Step 5 — Full Thickness Procedure Development

The objective of this step is to develop an electron beam welding procedure for both the horizontal and vertical positions for welding the full 8" thickness (one partial penetration weld from each side).

Step 6 — Starting/Stopping Procedure Development

The objective of this step is to develop a partial penetration weld starting and stopping procedure for both welding positions.

Step 7 — Development of Arc-Out Repair Technique

The objective of this step is to develop, for both welding positions, an acceptable welding procedure for repairing a weldment which experienced an arc-out.

Step 8 — Demagnetization Procedure Development

The objectives of this step are to: 1) determine the magnetic field strength necessary to displace a 4" deep electron beam weld by 0.100" (transversely with respect to the weld joint), 2) determine if SA387 plates could possess a residual magnetic field strength in excess of that determined above, and 3) develop and demonstrate, if necessary, a demagnetization device and/or procedure for reducing the residual magnetic field to a strength less than that determined above.

Step 9 — Determination of Joint Fit-Up Requirements

The objective of this step is to determine the joint gap width, the joint mismatch, and their combinations that can be acceptably welded without alteration of the welding procedure.

Step 10 — Laboratory Demonstration

The objective of this step is to produce an electron beam welded joint in both the horizontal and vertical positions, in 8" thick SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) acceptable to the ASME Boiler and Pressure Vessel Code Section VIII, Division 2.

Step 11 — Determination of Mechanical Properties

The objective of this step is to provide additional mechanical property data to that required by the ASME Boiler and Pressure Vessel Code Section VIII, Division 2. Tensile, bend, Charpy V-notch, hardness, and drop weight tests will be performed at various locations through the thickness in both the as-welded and stress relieved conditions.

Step 12 — Quarterly Reports

This step identifies the preparation and submission of quarterly reports.

Step 13 – Final Report

This step identifies the preparation and submission of the final report.

2.0 SUMMARY OF PROGRESS TO DATE

Figure 1 indicates the progress made through March 1978.

Step 1 – Planning

Complete.

Step 2 – Material Procurement

A sufficient amount of material required for performance of this project has been ordered but not yet received. Delivery is presently scheduled for April 17, 1978. This delivery date represents a three month delay from the planned delivery date of January 9, 1978. This delay will result in not completing the project within the scheduled time.

At present, communications with the vendor indicate that the material has been tested and is acceptable. The vendor is presently cutting the large plates into the required pieces and will subsequently ship the order.

Step 3 – Partial Penetration Procedure Development

Although scheduled, no work was performed on this step since the material was not received.

Step 8 – Demagnetization Procedure Development

It was calculated that a 4 gauss magnetic field was sufficient to displace an electron beam by 0.100" (an amount judged as detrimental) after 4" of travel in a vacuum. The maximum residual magnetic field strength of 2-1/4 Cr-1 Mo material was determined to be about 300 gauss. It appeared to be necessary to reduce (demagnetize) the residual magnetic fields of the plates to a strength of 4 gauss or less. However, it was shown experimentally that no demagnetization of the plates is required or necessary to permit proper fusion. 2-1/4 Cr-1 Mo plates cannot possess a residual magnetic field strong enough to displace the electron beam, and hence the fusion zone, within the metal. Welds were made in steel specimens containing a magnetic field of a strength equal to the maximum residual magnetic field strength of 2-1/4 Cr-1 Mo (300 gauss). No displacement of the fusion zone was observed. Within the metal, the electron beam can be thought of as operating in a magnetic void. Above the metal, however, where the electrons of the electron beam proceed toward the weld joint, the presence of a relatively small (1 gauss) magnetic field is sufficient to cause improper weld placement. To eliminate this potential condition a magnetic shield, for protection of the electron beam, was designed, fabricated,

and tested. This device prevented magnetic interaction with the electron beam for field strengths of up to 40 gauss. It appears unlikely that fields of this magnitude (40 gauss) would exist between the weld joint and the electron gun. Thus, a "demagnetization procedure" has been developed. The magnetic shield should be used if the magnetic field strength between the electron gun and the weld joint is greater than about 1 gauss. No demagnetization of the plates is necessary.

Step 12 -- Quarterly Reports

The first quarterly report was prepared and issued.

No work was performed on any of the other steps (4-7 and 9-13) as no work was planned.

FIGURE 1. PROJECT SCHEDULE

FORM EPC-A 535
12/1/77

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
MILESTONE PLAN AND MANAGEMENT REPORT

CRD 1013

PAGE 1

1. The first step is to identify the problem or question being asked.

1. Contract Agency Division ELECTRON BEAM WELDING - FIELD FAB THICK-WALLED PRESSURE VESSELS		2. Reporting Period through		3. Contract Number EF-77-C-01-2606													
4. Contractor Name, Address THE BABCOCK & WILCOX COMPANY CONTRACT RESEARCH DIVISION PO BOX 835 ALLIANCE, OHIO 44601				5. Contract Start Date 19 SEPTEMBER 1977 6. Contract Completion Date 19 MARCH 1979													
7. Item Name STEP		8. Reporting Category (i.e., contract line item or work breakdown structure element)		9. Fiscal Years and Months <div style="display: flex; justify-content: space-around;"> 1977 1978 1979 </div> <div style="display: flex; justify-content: space-around; font-size: small;"> SONDJFMAMJJASONDJFMAMJJ </div>												10. Period Comm.	
1		PLANNING															
2		MAT'L PROCUREMENT															
3		PARTIAL PENETRATION															
4		VACUUM LEVEL															
5		FULL THICKNESS															
6		START/STOP															
7		ARC-OUT															
8		DEMAGNETIZATION															
9		FIT-UP															
10		LAB DEMONSTRATIONS															
11		MECH. PROPERTIES															
12		QUARTERLY REPORTS															
13		FINAL REPORT															
11. Remarks: PQ = PROCEDURE QUALIFICATION																	
12. Signature of Contractor's Project Manager and Date EDWARD L. H. VANCE														13. Signature of Government Technical Representative and Date J. L. RYAN - 10-9-79			

3.0 DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Step 1 — Planning

Complete.

Step 2 — Material Procurement

As reported in the first quarterly report, a purchase order was issued on November 15, 1977 to purchase a sufficient amount of material to be used in this project. Blocks of various sizes with a thickness of 6" and 8", totaling 34,000 pounds, were ordered. A complete description of the purchasing requirements was given in the first quarterly report.

The planned delivery date for receipt of this material was January 9, 1978. The material has not yet been received. The vendor has cited several difficulties encountered in attempting to fulfill the order. Recent conversations indicate that the plate material has been rolled to the appropriate thicknesses, heat treated, tested, and found to be acceptable. Presently the plates are being cut to the required sizes as stated in the purchase order. Based on these conversations, we anticipate receiving the shipment of material on or before April 17, 1978. To date, a three month delay has been experienced. This delay will result in not completing the project within the scheduled time. An extension in the project completion date will be requested. The amount of extension, however, has not yet been determined.

Step 3 — Partial Penetration Procedure Development

Although scheduled, no work was performed during this period since the material was not received.

Step 8 — Demagnetization Procedure Development

Introduction

An electron in the presence of a magnetic field will experience a force that will move the electron. During electron beam welding, the kinetic energy of the electrons is dissipated in the form of heat to cause melting. In joining two pieces, it is essential that the fusion zone consume the butting surfaces of the weld joint. Improper placement of the fusion zone produces lack-of-fusion as a portion of the weld joint is not fused. Concern

over missing a portion of the weld joint due to magnetic displacement of the electron beam resulted in identifying a need to develop a procedure for assuring that the fusion zone is not inadvertently misplaced.

This project is intended to develop electron beam welding procedures for welding 8" thick SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) steel. From each side, a weld in excess of 4" penetration is planned. It was judged that if the electron beam were aligned with the weld joint at the surface, that a transverse displacement of the fusion zone of 0.100" or more after 4" of penetration would be unacceptable. From this the objectives of this step were formulated: 1) determine the magnetic field strength necessary to displace a 4" deep electron beam weld by 0.100" (transversely with respect to the weld joint), 2) determine if SA387 plates could possess a residual magnetic field strength in excess of that determined above, and 3) develop and demonstrate, if necessary, a demagnetization device and/or procedure for reducing the residual magnetic field to a strength less than that determined above.

Procedures & Results

The material of interest in this program is SA387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) steel, which is a ferromagnetic material. Ferromagnetic materials are characterized by a large intensity of magnetization with the application of a small magnetic field (magnetomotive force). The tendency of this magnetization to saturate as the field is increased, existence of a remnant magnetization and coercive force, and hysteresis of the magnetization curve are characteristics of ferromagnetic materials. These concepts are depicted in Figure 2.

If initially the material is non-magnetized, virgin material, and a magnetizing force, H , less than that required to saturate the material is applied in a cyclic manner; curve a will result. If the magnetizing force is sufficient to cause saturation, the large curve b results. On removal of the magnetizing force, the material will be left with some residual field, B_R . To reduce this remnant to zero, a magnetizing force equal to the coercive force must be applied in the opposite direction. If a magnetizing force less than the coercive force is applied in a cyclic manner, then curve c results. From this behavior, it follows that B_R is the maximum residual that the material can have and that a decaying magnetic force initially greater than that necessary to saturate the material is required for effective demagnetization.

FIGURE 2 MAGNETIC FLUX DENSITY (B) VERSUS MAGNETIC FIELD INTENSITY (H)

Since the material of interest can possess a residual magnetic field, the magnitude and direction of this residual field must be considered. The deflection of an electron beam can be determined by considering the force on an electron moving through a magnetic field. From Lorentz's Law, $\vec{F} = q\vec{v} \times \vec{B}$, it can be seen that the force will be largest when the electron is moving perpendicular to the magnetic field. Further, since the cross product of the velocity and the magnetic field is involved, the deflection will be perpendicular to both.

The major concern with displacement of the electron beam due to interaction with magnetic fields is the displacement that is transverse to the weld joint. Since the electron beam is parallel to the weld joint (through thickness), the most effective component of the magnetic field for transverse displacement of the electron beam will be the component along the length of the weld joint.

Such a component can be produced in several manners. Consider two sections which are to be welded together as being magnetized parallel to the faces which are to be welded (see Figure 3). The result is that there is a strong magnetic component directed along the weld joint. If instead one of the plates is turned around so that the residual field in its direction is in the opposite direction, there will be some cancelling. Just how strong a magnetic component results depends upon the difference in the magnitude of the two fields.

FIGURE 3 MAGNETIC LINES SURROUNDING TWO PLATES WHICH ARE TO BE WELDED TOGETHER
(TOP VIEW AS SEEN BY ELECTRON BEAM SOURCE).

Another way the component can result is illustrated in Figure 4. Here the two plates have residual fields perpendicular to the faces that are to be welded together. In this case, the strongest component along the weld seam will result when the two residuals are at equal magnitude. When the residuals in the plates are in the same direction, the component along the weld seam will be zero.

FIGURE 4 MAGNETIC LINES SURROUNDING TWO PLATES WHICH ARE TO BE WELDED TOGETHER
(TOP VIEW AS SEEN BY ELECTRON BEAM SOURCE).

In general, the direction as well as the magnitude of the residual magnetic field will be randomly distributed. Various situations as described above and any combination thereof can occur. This being the case, the deflection of the electron beam transverse to the joint could be large or insignificant. In any case, the arrangement of two pieces in preparation for welding will determine the magnitude and direction of the resulting magnetic field.

An experiment was conducted to determine the maximum residual magnetic field that could be obtained in the 2-1/4 Cr-1 Mo material. This was accomplished by winding 800 turns around a 6-1/2 inch length bar of 1-1/2" diameter of 2-1/4 Cr-1 Mo material and applying a DC current of 8 amperes. The magnetomotive force applied then was of the order of 40,000 ampere-turns/meter. This magnetomotive force should have saturated the sample and produced the maximum residual magnetic field. After magnetization, the magnetic field at the end of the bar was measured to be about 300 gauss.

Next, the effect on the magnitude of the residual magnetic field was determined as a function of temperature. It was felt that perhaps the preheating associated with welding of the part could be used to obtain a reduction in the residual field. The following table identifies the results of this experiment:

<u>Temperature</u>	<u>Time of Soak</u>	<u>Residual Field</u>
75°F	—	295 gauss
250°F	4 hours	280 gauss
300°F	7 hours	260 gauss
400°F	7 hours	220 gauss

As expected, elimination of the residual field was not obtained since the temperatures involved were considerably less than the curie point of the material. Thus, preheating as a means of reducing residual magnetic fields is not effective.

The results of these experiments show that the maximum residual magnetic field obtainable in 2-1/4 Cr-1 Mo is about 300 gauss. In welding 2-1/4 Cr-1 Mo steel, this potential level of magnetism must be considered.

The magnitude of the residual magnetic field required to deflect a 4" deep electron beam weld 0.100" was determined. To do this, the interaction of an electron beam and a magnetic field was modeled.

The model is depicted in Figure 5 and consists of an electron accelerated through a potential ($V = 60$ kv) and passing through a region ($L = 4$ ") over which a uniform magnetic field (B) is applied in a direction perpendicular to the direction in which the electron is moving. In reality, we have an electron beam interacting with the material being welded. As the beam passes through the material, electrons collide with the metal atoms. The heat that results is sufficient to melt the material. Thus the material and the region through which the beam passes will be at a temperature greater than the curie point and will be non-magnetic. The residual field which can have any orientation, for this calculation, will be considered as acting on these electrons in vacuum.

FIGURE 5 MODEL OF MAGNETIC FIELD ACTING ON AN ELECTRON BEAM

Using the simplified model and applying Lorentz's Law for the force on a moving charge in a magnetic field, the expression for the deflection, d , of the electron beam is obtained as follows.

The energy gained by the electron by being accelerated through a potential, V , is essentially equal to its kinetic energy, i.e.,

$$eV = \frac{1}{2} mv^2 \quad \text{Eq. 1}$$

where e is the charge on the electron, V is the accelerating potential, m is the electron's mass, and v is the electron velocity. Yielding:

$$v = \sqrt{\frac{2eV}{m}}$$

From Lorentz' Law:

$$\vec{F} = e\vec{v} \times \vec{B} \quad \text{Eq. 2}$$

Because $\vec{v}$ is perpendicular to $\vec{B}$:

$$F = evB$$

The charge thus is accelerated at a rate:

$$a = \frac{F}{m} = \frac{evB}{m} \quad \text{Eq. 3}$$

Equations 1 and 3 result in:

$$a = B \frac{e}{m} \sqrt{\frac{2eV}{m}}$$

The displacement then is given by:

$$d = \frac{1}{2} at^2 \quad \text{Eq. 4}$$

Since:

$$t = \frac{L}{V}$$

then:

$$d = \frac{1}{2} a \left(\frac{L}{V}\right)^2 = \frac{1}{2} \cdot \frac{eVB}{m} \cdot \frac{L^2}{V^2}$$

or:

$$d = \frac{1}{2} L^2 B \sqrt{\frac{e}{2mV}}$$

Eq. 5

Equation 5 gives the deflection of an electron beam traveling perpendicularly through a magnetic field. To determine the magnetic field strength necessary to displace an electron beam by 0.100" after 4" of travel, the following calculation is made:

For an electron $e = 1.6 \times 10^{-19}$ coulomb and $m = 9.108 \times 10^{-31}$ kg. An accelerating potential of 60,000 volts is used.

$$\sqrt{\frac{e}{2mV}} = 12.1 \times 10^2$$

$$L^2 = (4 \times 0.0254)^2$$

$$d = (0.100 \times 0.0254)$$

thus:

$$B = \frac{2 \times 2.54 \times 10^3}{1.032 \times 10^{-2} \times 12.1 \times 10^2}$$

$$= 4.06 \times 10^{-4} \frac{\text{webers}}{\text{m}^2}$$

$$= 4.06 \text{ gauss}$$

From this calculation, it was learned that a magnetic field of only 4 gauss would be sufficient in vacuum to move an electron beam .100" after 4" of travel. An experiment was performed to verify this computed displacement. Here, an electromagnet was constructed which contained pole faces that were 4" x 2". A gap of 1/4" between the pole faces was used. Two coils made of 247 turns each, were connected in series to supply the magnetic field. The current supply was a Fluke Calibration Standard Model 382A. Magnetic fields

were measured with a RFL Industries Model 505 Gaussmeter with a 1/16" thick probe. The apparatus was positioned so that the electron beam would pass through the magnetic field (1/4" gap) in the 4" dimension, and then strike a plate. Figure 6 is a photomicrograph of the electromagnet used and the arrangement of the components for the test. The electron beam was focused onto the surface of the test plate and was operated at a few milliamperes of current, sufficient to engrave the surface of the plate. The magnetic field was varied and the position or displacement of the electron beam was then engraved on the plate. Measurements were then taken of the displacement as a function of the magnetic field. Figure 7 is a photograph of the engravings obtained in the test. The results of this test are listed below.

<u>Magnetic Field (Gauss)</u>	<u>Electron Beam Displacement (Inches)</u>
1	0.015
2	0.042
3	0.072
4	0.102
5	0.132
6	0.166
7	0.188
8	0.212

From this it was learned that indeed a 4 gauss field was sufficient to displace an electron beam .100" after 4" of travel in a uniform magnetic field in vacuum. Thus, as expected, experimental confirmation of the predicted or calculated behavior was obtained. The experiment also confirmed the accuracy of the gaussmeter used to make the magnetic field measurements.

It was next decided to operate the electron beam in steel to observe the deflection in the presence of a known magnetic field. A 1" x 1" x 2" carbon steel sample was positioned between the pole faces of the electromagnet as shown in Figure 8. A 1/16" thick copper spacer containing a notch was used to a) minimize magnetic fringing, b) allow for insertion of the gaussmeter probe for magnetic field measurements (notch), and c) allow for intimate contact of the sample between the magnet's pole faces to support the weld sample without the insertion of other material between the pole faces. Figure 9 is a photograph showing the apparatus with the magnetic probe inserted for making magnetic field measurements.

Figure 6. Photograph of electromagnet (4"x2" pole faces), with 1/4" gap used to determine electron displacement as a function of magnetic field strength.

Figure 7. Photograph showing engravings (displacement) obtained with various magnetic field strengths.

Figure 8. Photograph showing arrangement of 1"x1"x2" carbon steel weld sample between pole faces of the electromagnet.

Figure 9. Photograph showing probe inserted in notched copper spacer for measurement of the magnetic field strength.

Using the relationship previously developed (Equation 5), the displacement of the electron beam is proportional to the magnetic field strength multiplied by the depth of travel squared ($d \propto BL^2$). If a 4 gauss field were sufficient to displace a 4" deep weld by 0.1", then it follows from the relationship that a 256 gauss field would be sufficient to displace a 1/2" deep weld by 0.1". Thus a field of 256 gauss was produced in the steel sample during welding. The weld sample was cross sectioned, polished and etched, and the fusion zone observed. It was observed that the weld was straight and was not affected by the presence of the magnetic field. Figure 10 is a photomicrograph of a cross section taken from the sample. The magnetic field which should have displaced this weld by 0.1" was observed to have no effect.

It was observed that as the beam exited the sample at the 1/16" gap area, where magnetic fringing occurred, a considerable motion or displacement of the fusion zone was encountered. Figure 11 is an end view of two samples where the beam exited the steel. With the electron beam operating inside the steel in a uniform magnetic field, no interaction with the magnetic field was experienced. However, as the electron beam encountered the end of the sample and began operating in vacuum, the fusion zone was dramatically displaced. It appeared that the magnetic state within the steel itself was inconsequential. However, the fringing or the amount of magnetic field above the surface of the weldment could cause the beam to move prior to entering the metal.

A calculation was performed to determine the magnetic field strength between the electron gun and the workpiece surface which would be sufficient to alter the trajectory of the electron beam so that the fusion zone after 4" of penetration would be displaced by 0.100". Figure 12 depicts the displacement of the fusion zone due to magnetic fields between the plate's surface and the electron gun. As the electrons proceed from the gun to the plate along length L , their trajectory is altered by magnetic field B , such that the angle of incidence is no longer normal to the plate's surface (i.e., parallel with the weld joint). If the electron beam were directed such that a .100" weld displacement after 4" of travel were obtained, the angle of entry of the electron beam must be $\tan^{-1} (.1/4) = 1.432^\circ$. Taking the partial derivative of displacement given in Equation 5 with respect to L , an equation is derived which will give the angle of incidence.*

Figure 10. Photomicrograph of a cross section of a 1/2" deep electron beam weld made with a 256 gauss field in the metal during welding.

Figure 11. Photograph showing end view of welded samples where the beam exited the material. Note the displacement as the electron beam enters the "air gap" (leaves the metal).

Thus, for a gun-to-work distance (L) of 6" the magnetic field of 1 gauss is sufficient to displace the weld zone by 0.1" after 1" of penetration is gained. Obviously, as the gun-to-work distance increases, the magnetic field strength to cause improper fusion decreases. Consequently, a very small magnetic field existing between the electron gun and the weldment's surface will be sufficient to cause misplacement of the electron beam weld.

From the previous welding experiments it appeared that the residual magnetic field within the metal would have little consequence, however, depending upon the arrangement of the electron gun, magnetic shielding, and return flux existing between the electron gun and the surface of the plate, a sufficient field might be induced to deflect the electron beam (and therefore the fusion zone). Hence, it was felt necessary to design a magnetic shield to be used for protecting the electron beam between the electron gun and the work surface.

Toward this end, a magnetic shield was designed and constructed. Figure 12 is a photograph of the conical magnetic shield. The material (Mu metal) used in construction of the shield is a highly permeable material which also exhibits a minimum residual magnetic field. With the Mu metal surrounding the electron beam, the magnetic strength must travel through the Mu metal rather than proceeding through the air. Thus, the magnetic field is concentrated along the axis of the gun. The shield is 4" in diameter and 1" in height. The magnetic field around the electron gun, in the region of the electron beam with the shield, is directed along the axis of the gun.

FIGURE 12. MODEL OF ELECTRON BEAM IN A MAGNETIC FIELD CAUSING THE ELECTRON BEAM TO ENTER THE WORK SURFACE AT AN ANGLE OF INCIDENCE, a

Figures 14 and 15 show the electron gun with and without the magnetic shield. During operation, the electron gun with the magnetic shield is positioned above the weld joint so that the distance between the end of the shield and the workpiece surface is approximately 1/2" (reasonably close to the surface yet far enough away to avoid touching the molten weld metal).

An experiment was conducted to verify the effectiveness of the magnetic shield. The electromagnet used previously was modified to have a 2" x 6" gap between the 4" x 2" pole faces. The electron gun was then energized and the magnetic field was induced in the center of the pole faces. The electron beam, which was 1/8" in diameter, struck a plate of metal, striking a plug.

This equation can then be solved for the magnetic field strength (B) which would cause the electron beam to enter the plate in such an angle as to cause a fusion zone displacement of 0.100" after 4" of penetration.

$$d = \frac{1}{2} BL^2 \sqrt{\frac{e}{2mV}} \quad \text{Eq. 5}$$

The angle α (tangent to the electron's trajectory at the metal surface) which displaces the weld 0.100" after 4" of penetration is:

$$\alpha = \tan^{-1} \left(\frac{0.1}{4} \right) = 1.432^\circ$$

This angle is equal to the partial derivative of d with respect to L giving:

$$\alpha = \frac{\partial d}{\partial L} = LB \sqrt{\frac{e}{2mV}}$$

Solving for B:

$$B = \frac{\alpha L}{\sqrt{\frac{e}{2mV}}} \quad \text{Eq. 6}$$

Substituting $L = 6"$ (typical gun-to-work distance) and $V = 60,000$ volts, and solving for B yields:

$$\sqrt{\frac{e}{2mV}} = 12.1 \times 10^2$$

$$\alpha = 1.432^\circ = 1.75 \times 10^{-2} \text{ rad.}$$

$$L = 6 \times 2.54 \times 10^{-2} \text{ m}$$

$$B = \frac{1.75 \times 10^{-2} \times 6 \times 2.54 \times 10^{-2}}{12.1 \times 10^2}$$

$$= 0.95 \times 10^{-4} \frac{\text{webers}}{\text{m}^2}$$

$$= 0.95 \text{ gauss}$$

Thus for a gun-to-work distance (L) of 6" the magnetic field (B) necessary to displace the weld zone by 0.1" after 4" of penetration is 1 gauss. Obviously as the gun-to-work distance increases, the magnetic field strength to cause improper fusion decreases. Consequently, a very small magnetic field existing between the electron gun and the weldment's surface will be sufficient to cause misplacement of the electron beam weld.

From the previous welding experiments it appeared that the residual magnetic field within the metal would be of little consequence. However, depending upon the arrangement of the pieces being welded, magnetic fringing, and return flux existing between the electron gun and the surface of the plate, a sufficient field might be present which would cause displacement of the electron beam (and therefore the fusion zone). Hence, it was felt necessary to design, fabricate, and test a device for protecting the electron beam between the electron gun and the work surface.

Toward that end, a cone was made of 0.030" thick Mu metal. Figure 13 is a photograph of the conical magnetic shield. The material (Mu metal) used in construction of the magnetic shield is a highly permeable material which also exhibits a minimum residual magnetic field. With the Mu metal surrounding the electron beam, a magnetic field would travel through the Mu metal rather than proceeding through vacuum to interact with the electron beam. Thus, magnetic fields are diverted around the electron beam (which is operating along the axis of the cone). With the magnetic shield essentially shunting the magnetic field around the electron beam, no interaction of the electron beam with the magnetic field is obtained.

Figures 14 and 15 show the electron gun with and without the magnetic shield. During operation, the electron gun with the magnetic shield is positioned above the weld joint so that the distance between the end of the shield and the workpiece surface is approximately 1/2" (reasonably close to the surface yet far enough away to avoid touching the molten weld metal).

An experiment was conducted to verify the effectiveness of the magnetic shield. The electromagnet used previously was modified so that a 2-1/8" gap between the 4" x 2" pole faces was obtained. The electromagnet was then energized and the magnetic field was measured in the center of the pole faces. An unprotected electron beam was passed through the 2" dimension of the magnetic field striking a plate.

Figure 13. Photograph of the conical magnetic shield (the electron beam passes along the axis of the cone).

Figure 14. Photograph of electron gun without magnetic shield.

Figure 15. Photograph of electron gun with magnetic shield.

Engravings, produced by the electron beam, on the plate were then measured and the displacement recorded for different magnetic fields. The experiment was then repeated by inserting the magnetic shield between the pole faces. Figure 16 is a photograph which illustrates the test set-up. Figures 17 and 18 respectively are photographs of the engraved plates made with and without the magnetic shield. The difference in displacement with and without the magnetic shield is striking. The following table summarizes the results of this experiment:

<u>Magnetic Field (Gauss)</u>	<u>Displacement w/o Shield (Inches)</u>	<u>Displacement w/Shield (Inches)</u>
0	.000	.000
10.5	.015	.000
20.5	.027	.000
30.0	.037	.000
40.0	.050	.000
50.0	.065	.005
60.0	.078	.010
70.0	.095	.024
80.0	.115	.040
90.0	.137	.060
100.0	.175	.100

It was apparent that the magnetic shield was effective at preventing unwanted electron displacement for magnetic fields of 40 gauss or less. The data also showed that the magnetic shield is saturated at about a 50 gauss level and thus allows a magnetic field to interact with the electron beam to cause beam displacement. It would appear unlikely to obtain a 40 gauss field above the surface of a component whose maximum residual is 300 gauss. It thus appears that the magnetic shield would be very effective at eliminating the effects of magnetic fields above the surface of a part to be welded. If a magnetic field in excess of 40 gauss were experienced, it would only necessitate the fabrication of a thicker magnetic shield.

Before the final thickness of the Mu metal shield can be made, measurements of the magnetic field experienced between the electron gun and the weldment will be made throughout this project. This will indicate the maximum amount of field that can be anticipated in practice.

Figure 16. Photograph showing magnetic shield between pole faces of the electromagnet.

Figure 17. Photograph showing engravings made by the electron beam operating in a magnetic field without the magnetic shield. Engraved dots are at 10 gauss intervals. (Magnified at 2.2X)

Figure 18. Photograph showing engravings made by the electron beam operating in a magnetic field with the magnetic shield. Engraved dots are at 10 gauss intervals. (Magnified at 2.2X)

An additional experiment was performed with the Mu metal positioned between the magnetic poles. Here, the magnetic probe of the gaussmeter was inserted to the center of the Mu metal shield. The magnetic field was increased to the point where the measured field was 1.0 gauss. The Mu metal shield was then removed from the magnet and the magnetic field strength measured. A measured value of 63 gauss was obtained which produced a 1.0 gauss field in the interior of the magnetic shield.

Another experiment was conducted to demonstrate that welds can be made on material magnetized to the maximum residual field obtainable in 2-1/4 Cr-1 Mo. This was accomplished using two 1" x 1" x 2" carbon steel specimens arranged to form a weld joint. The specimens were positioned between the pole faces of the magnet as indicated in Figure 19. Again, the 1/16" diameter notched copper spacer was used. A procedure for making a 1" deep weld was obtained. Using the previously developed relationship of $d \propto BL^2$, a magnetic field of 4,800 gauss was used for the 1" deep weld which would represent the same displacement (0.100") obtained at 300 gauss (maximum residual of 2-1/4 Cr-1 Mo) on a 4" deep weld. Weld joints were aligned parallel with the magnetic field and transverse to the magnetic field. The welds were then made, cross sectioned, polished, and etched. Figure 20 is a photomacrograph of the weld made with the magnetic field parallel with the weld joint. It can be seen that the weld joint was properly fused and that the electron beam weld was not affected by the 4,800 gauss field. Figure 21 is a photomacrograph of a 1" deep weld where the magnetic field was transverse to the weld joint. Again, the weld joint was properly fused and no displacement of the electron beam fusion zone was experienced. Thus, welds were made, simulating a 4" deep weld with the maximum residual magnetic field (300 gauss) obtainable in 2-1/4 Cr-1 Mo. Neither the magnitude or the direction of the magnetic field was sufficient to cause displacement of the electron beam weld. Although this experiment was designed to model a 4" deep weld, in actuality a magnetic field of 4,800 gauss was used. This also showed that for fields as high as 4,800 gauss no displacement in a 1" deep weld was obtained.

Figure 19. Photograph showing weld test sample (containing a weld joint) positioned between pole faces of electromagnet. Test samples were welded with a 4800 gauss field in the steel with the weld joint positioned both parallel and transverse to the magnetic field.

Figure 20. Photomicrograph of a 1" deep EB weld made with a 4800 gauss field parallel to the weld joint. No displacement of the fusion zone was observed and proper joint fusion resulted.

Figure 21. Photomicrograph of a 1" deep EB weld made with a 4800 gauss field transverse to the weld joint. No displacement of the fusion zone was observed and proper joint fusion resulted.

Discussion

Consideration of the effect or influence of magnetic fields in the placement of the fusion zone during electron beam welding has been made. It was determined that a maximum residual magnetic field of 300 gauss could be experienced with 2-1/4 Cr-1 Mo steel. It was computed and verified experimentally that a 4 gauss magnetic field would be sufficient to displace an electron beam 0.100" after 4" of travel in vacuum. Thus, it was apparent that a potential problem could exist in appropriately fusing the weld joint.

Reducing the residual magnetic fields in the large plates anticipated for fabrication of coal gasification units is difficult. Often large fields are produced when manufacturers of steel plate handle the plates with electromagnets. Existing methods for demagnetization of large plates use extremely large DC current sources and progressively reduce the magnitude and alternate the polarity of the demagnetizing current so as to take the material through the B-H loop and produce a residual field of near zero. This can be a time consuming and expensive operation. Arc welding is subject to magnetic produced disturbances. It has been observed that magnetic fields of 10 gauss or more in the vicinity of a welding arc is sufficient to cause movement of the arc and hence improper welding.

The experiments conducted in this project show that there are two regions of interest during electron beam welding. The first being the displacement of the weld due to magnetic fields affecting the beam inside the metal. It was shown that no movement was obtained for magnetic field strengths up to the maximum residual of 2-1/4 Cr-1 Mo. Apparently the electron beam welding process operating inside the metal is such that the heated zone being both non-magnetic and less permeable than the surrounding material causes the magnetic flux to exist in the more permeable surrounding material and hence is removed from the electron beam. In essence, welding can be thought of as taking place in a magnetic void. Thus, no concern exists over the magnetic condition of the plates to be welded. Hence, no demagnetization procedure is necessary.

The other area of concern is the magnetic state between the electron gun (source of electrons) and the workpiece. It was shown that very small fields (e.g., 1 gauss) would be sufficient to misdirect the electron beam

at entry to the metal surface. If, after fit-up of the weld joint, a magnetic field between the gun and the joint is measured to exceed 1 gauss, then a magnetic shielding device must be used. Such a device was designed, fabricated, and tested. It was shown that for fields of up to 40 gauss no displacement of the electron beam was encountered. This magnetic shield is relatively inexpensive, easy to fabricate, and easy to attach to the electron beam welding gun. It appears to be very unlikely that a field strength of more than 40 gauss would be encountered. If it were, it would only mean that the magnetic shield should be made of thicker material to provide more shielding.

During the course of this project, the weld test pieces will be scanned to determine the maximum magnetic field obtained between the electron gun and the material. This will provide practical information as to the strength of fields experienced which can then be used in the design and fabrication of future magnetic shields. A final proof test is planned for later in the project by making 4" deep welds in 2-1/4 Cr-1 Mo material. No difficulty is anticipated in successfully demonstrating welding of joints composed of plates which exhibit residual magnetic fields (residual fields occurring as-received and due to customary magnetizing operations such as arc welding and magnetic particle inspection).

Conclusions

1. In a vacuum, an electron beam traveling 4" through a perpendicular 4 gauss magnetic field is displaced by 0.100".
2. The maximum residual magnetic field strength of 2-1/4 Cr-1 Mo steel is about 300 gauss.
3. The reduction in the residual magnetic field strength by heating the steel to temperatures up to 400°F will only slightly reduce the residual magnetic field strength.
4. During welding, the electron beam operating within the steel is not influenced by the presence of magnetic fields with strengths up to the maximum residual of 2-1/4 Cr-1 Mo steel.
5. 2-1/4 Cr-1 Mo steel cannot possess a residual magnetic field strong enough to displace the electron beam, and hence the fusion zone, within the metal. No demagnetization of the steel is necessary.

6. The electron beam operating between the source of electrons and the weldment surface is affected by the presence of a magnetic field which will misdirect or alter the angle of incidence of the electron beam with respect to the weld joint. Small magnetic fields (e.g., 1 gauss) can cause a significant displacement of the electron beam weld.

7. Should a magnetic field of 1 gauss or more be present at the time of welding between the electron gun and the plate surface, it is necessary to use a magnetic shield to protect the electron beam.

8. A magnetic shield was designed and fabricated which is sufficient to protect the electron beam, between the electron gun and the plate surface, from magnetic fields of up to 40 gauss.

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Step 12 - Quarterly Reports

The first quarterly report was prepared and issued.

No work was performed on any other steps, as no work was planned.

4.0 PLANNED WORK FOR NEXT REPORTING PERIOD

Step 1 — Planning

No work planned.

Step 2 — Material Procurement

The ordered material should be received. Scheduled delivery date is April 17, 1978.

Step 3 — Partial Penetration Procedure Development

Electron beam welds will be made on 6" thick SA387 Grade 22 Class 2. These welds will be partial penetration with a penetration of about 4-1/2". They will be cross sectioned and examined for the presence of defects. Based on the information obtained from the sectioned weld, the electron beam welding procedure will be modified and the process repeated. Several iterations of this process should result in a welding procedure that produces acceptable non-defective welds. This process will be repeated for three vacuum levels (approximately 0.06, 40, and 100 microns). The work performed during this period will concentrate on developing the required welding procedures in the horizontal welding position.

Steps 4-7

No work planned.

Step 8 — Demagnetization Procedure Development

The procedure for effectively dealing with the magnetic field associated with this material and thickness has been developed. No further development work is needed. However, during the remainder of the project, magnetic field measurements will be made on the pieces being welded to determine the strength of the field between the electron gun and the weldment surface. The magnetic shield developed to date will prevent electron displacement for fields of 40 gauss or less. It is anticipated that this field strength (40 gauss) will not be encountered. However, by measuring the field resulting from the plates used in the project, the largest field encountered will indicate whether the existing magnetic shield is adequate or whether a thicker magnetic shield is needed. A 4" deep welding demonstration of the effectiveness of the "demagnetization procedure" developed to date is not planned for the next reporting period.

Steps 9-11

No work planned.

Step 12 – Quarterly Reports

The second quarterly report will be issued.

Step 13 – Final Report

No work planned.