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

Third Quarterly Report, April 1—June 30, 1978

By
Charles M. Weber

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

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

U. S. DEPARTMENT OF ENERGY

MASTER

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

Third Quarterly Report for the
Period 1 April 1978 — 30 June 1978

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Prepared for the
Department of Energy
Division of Fossil Energy
Under Contract EF-77-C-01-2606

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ABSTRACT

This report is the third quarterly report of a project to develop and demonstrate an electron beam welding procedure for welding 8" thick SA 387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) steel. It covers the progress made during the period April-June 1978. The steel ordered for use on this project was received on April 17, 1978. The late arrival of the steel has resulted in a delay of the scheduled work.

Work is in progress for developing 4-1/2 inch deep partial penetration electron beam welding procedures. A total of 95 welds have been made to date in the horizontal position. A welding procedure which produces a defect-free weld has not been developed to date. Many difficulties have been encountered and all but one have been successfully overcome.

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 June 30, 1978.

Step 1 — Planning

Complete.

Step 2 — Material Procurement

A sufficient amount of SA 387 Grade 22 Class 2 (2-1/4 Cr-1 Mo) was received on April 17, 1978. The material has been certified by the vendor to conform to the requirements of SA 387 Grade 22 Class 2. 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.

Step 3 — Partial Penetration Procedure Development

A total of 95 partial penetration electron beam welds have been made to date in the horizontal position. Experimental welds were made on 6" thick plate where the penetration was 4" or greater. These welds were cross sectioned and the results observed. Modifications of the welding procedure were made and the process of sectioning and observing the results repeated.

Several difficulties have been encountered most of which have been satisfactorily resolved. When welding in the horizontal position, it was observed that the liquid metal would drain from the fusion zone which resulted in the formation of a large void in the weld. It was necessary to use a shelf to support the liquid metal at the surface of the plate. The use of the shelf was effective in reducing the size of the fusion zone voids but was not sufficient to eliminate this defect. It was also observed that the size, frequency, and pattern of beam oscillation influenced the size of the fusion zone voids; however, no welding procedure was developed which eliminated the presence of fusion zone voids. It was therefore felt necessary to incline the electron beam from the level horizontal position. Experiments were performed to define the preferred angle of inclination. Welds made with the beam inclined by 3° with respect to the level horizontal position did not contain the large fusion zone voids.

Welds were made at pressures of 25 microns to 100 microns. No beneficial effects were observed and contrarily, excessive soot and erratic equipment operation were encountered. All future work will be done using hard vacuum conditions.

Additional trials were made by altering the weld procedure in attempts to produce defect-free welds. Other defects which were encountered and which have been successfully eliminated are: root porosity, centerline solidification voids, and transverse fusion zone microcracking. However, the presence of a root crack (necklace defect) is still observed. Of the 95 welds examined to date, there have been no observations of any heat affected zone cracks or fissures.

In summary, welding procedure development work is in progress. Many difficulties have been overcome, but the final partial penetration welding procedure has not yet been developed.

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 second quarterly report was prepared and issued.

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

FIGURE 1. PROJECT SCHEDULE

FORM EPDA 535
(2/1/77)

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

CRD 1013

PAGE 1 OF 1

FORM EPDA 535
(2/1/77)

1. Contract Identification 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. Report Number	8. Reporting Category, i.e., contract line item or work breakdown structure & activity	9. Fiscal Years and Months												10. Percent Complete												
		1977				1978				1979																
STEP		S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J		
1	PLANNING	■																								
2	MAT'L PROCUREMENT	■																								
3	PARTIAL PENETRATION					■				△																
4	VACUUM LEVEL									△																
5	FULL THICKNESS									L		△														
6	START/STOP											L		△												
7	ARC-OUT													L		△										
8	DEMAGNETIZATION			■		■						DEMO	△													
9	FIT-UP														L		△									
10	LAB DEMONSTRATION												L	△	△											
11	MECH. PROPERTIES													L		△										
12	QUARTERLY REPORTS			■			■				△		△		△		△									
13	FINAL REPORT																	L	△							

11. Remarks **PQ - PROCEDURE QUALIFICATION**

12. Signature of Contractor's Project Manager and Date

FRANK L. HAYALICO

Final Report 10/77

13. Signature of Government Technical Representative and Date

3.0 DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Step 1 — Planning

Complete.

Step 2 — Material Procurement

As reported in the first and second quarterly reports, 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 ordered material was received on April 17, 1978. This material was produced by electric furnace melting followed by pouring to a 165 ton ladle and vacuum degassing. A portion of the melt was rolled to the required 6" and 8" thicknesses. The plates were normalized at 1650-1700°F, held for one hour per inch of thickness minimum, then air cooled. The plates were then tempered at 1260°F, held at temperature for 3/4 hour per inch of thickness minimum followed by air cooling. The chemical analyses of both the ladle and the plates are given in Table 1.

Table 2 gives the mechanical properties of the ordered material. For each plate, test coupons were tested in the stress relieved condition. Stress relief was accomplished by heating to 1250-1300°F, held for 20 hours, and furnace cooled within a rate of 40°F per hour to 600°F following by air cooling.

This normalized and tempered material has been certified by the vendor to conform to the requirements of the 1977 edition of the ASME Code Section II, Specifications for SA 387 Grade 22 Class 2 and Section VIII, Division 2, Articles M-1 and M-2 and has been ultrasonically inspected to AM-203-1.

This material was received three months later than planned. This delay will result in not completing the project in the scheduled time. An extension in the scheduled completion date will be requested. The amount of the extension, however, has not yet been determined.

TABLE 1

CHEMICAL ANALYSIS OF THE SA 387 GRADE 22 CLASS 2 MATERIAL⁽¹⁾

	<u>%C</u>	<u>%Mn</u>	<u>%P</u>	<u>%S</u>	<u>%Cu</u>	<u>%Si</u>	<u>%Ni</u>	<u>%Cr</u>	<u>%Mo</u>	<u>%V</u>	<u>%Ti</u>	<u>%Al</u>	<u>%O</u>	<u>%N</u>	<u>H</u> ⁽²⁾
6" Thick Plate															
Ladle	.12	.45	.017	.019	.10	.11		2.18	.97						
Check	.10	.45	.011	.020	.10	.11	.12	2.16	.97	.00	.002	.001	.0072	.0113	1.7
8" Thick Plate															
Ladle	.12	.45	.017	.019	.10	.11		2.18	.97						
Check	.10	.44	.017	.016	.10	.11	.13	2.15	.95	.00	.002	.001	.0080	.0093	1.2

(1) Electric furnace melt and vacuum degassed; melt #D5792.

(2) Values given in PPM.

TABLE 2
MECHANICAL PROPERTIES OF THE SA 387 GRADE 22 CLASS 2 PLATES

	<u>Yield Strength (ksi)</u>	<u>Tensile Strength (ksi)</u>	<u>% Elongation in 2"</u>	<u>% Reduction of Area</u>	<u>CVN Impacts⁽²⁾ (ft-lbs)</u>
6" thick plate	61.8	87.4	24	68.9	118 110 116
8" thick plate	55.7	76.0	25	69.0	100 110 110

(1) Plates and tests normalized 1650-1700°F, held 1 hr per inch min. and air cooled, then tempered 1260°F, held 3/4 hr per inch min. and air cooled. Tests stress relieved by heating to 1250-1300°F, held 20 hrs. and furnace cooled within a rate of 40°F per hr. to 600°F. Grain size 3-4. Test specimens taken from 1/4T location.

(2) Tested at +50°F.

Step 3 – Partial Penetration Procedure Development

Introduction

The objective of this project is to develop and demonstrate an electron beam welding procedure for welding 8" thick SA 387 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. To achieve this objective, it is necessary to first develop an appropriate welding procedure. The approach taken will be to weld the full 8" thick plate by using a 2 pass welding technique, one pass from each side of the plate. Thus, it is necessary to first develop a partial penetration procedure which is capable of making satisfactory welds slightly in excess of 4" penetration. The objective of this step is to develop the electron beam welding procedures for making partial penetration welds (approx. 4-1/2" deep) at three vacuum levels (approx. 0.06, 40, and 100 microns) in both the horizontal and vertical positions. A trial and error experimental approach is used to develop the partial penetration procedures. During this reporting period, work was performed to develop the partial penetration welding procedure in the horizontal welding position. This report presents the results of this effort to date.

Results & Discussion

Figure 2 is a sketch showing electron beam welding in the horizontal position. All of the procedure development work presented in this report was performed on the 6" thick SA 387 Grade 22 Class 2 material. To date, a total of 95 experimental welds have been made. Numerous difficulties have been experienced and overcome in an attempt to make an acceptable weld.

FIGURE 2 SKETCH SHOWING ELECTRON BEAM WELDING IN THE HORIZONTAL POSITION

Figure 3. Photomacrograph of an etched cross-section showing partial penetration welds #1, #2, and #3 made in the horizontal welding position. (Note the metal drainage from the fusion zone.)

Figure 3 is a photograph showing three partial penetration welds in a 6" plate. It was learned from this trial that during welding the liquid metal in the weld pool being unsupported at the plate surface was draining from the weld pool. The effect on the weld from this loss of material was the presence of large holes or voids in the fusion zone. To counteract this effect, a shelf was attached to the surface of the weldment which supports the liquid metal and allows freezing to take place without excessive draining from the weld pool. Figure 4 is a schematic showing the arrangement of the shelf. Numerous trials were then performed using the attached shelves. Modifications were made to beam current, travel speed, focus location, gun-to-work distance, and beam oscillation (pattern, size, and frequency). The shelves were effective at reducing the amount of metal coming from the weld pool. However, an excessive amount still appeared which resulted in the formation of voids within the weld. For example, Figure 5 shows welds made with the use of a shelf. In comparison with Figure 3, it is observed that the size of the voids were reduced, but they were not eliminated.

FIGURE 4 SKETCH SHOWING HORIZONTAL ELECTRON BEAM WELDING USING A SHELF

In addition to altering the above mentioned weld parameters, the vacuum pressure was increased to various levels to observe the effect. Figures 6 and 7 show the arrangement of the welding equipment for operating in the partial pressure vacuum regime. It was observed that welding with increasing pressures up to 50 microns was not influential on the presence or size of voids encountered. It was observed that when welding using 25 to 50 microns pressure that the electron gun operation became very erratic and unstable — frequent arcing was experienced. And, as shown in Figures 6 and 7, a tremendous amount of a sooty deposit was produced.

Figure 5. Photomacrograph of an etched cross-section showing partial penetration welds #36, #37, and #38 made in the horizontal welding position. (Use of the support shelf retards fusion zone drainage resulting in smaller voids (Ref. Fig. 3).

Figure 6. Photograph showing vacuum chamber interior with soft vacuum gun adaptor for welding in pressures of 25 micron or higher. (Note excessive sooty deposit produced when welding at pressures of 25 microns or higher.)

Figure 7. Photograph showing close-up of electron gun and 6" thick sample containing three trial welds. (Arrangement shows pumping adaptor for use in soft vacuum welding of pressures of 25 microns or higher. Note the presence of sooty deposits when welding with soft vacuum conditions (25 microns or higher.)

Attempts to weld at a higher pressure of 100 microns were not successful, as our equipment would not operate at that pressure level. The presence of a relatively large amount of sooty deposits (although these sooty deposits were not analyzed, previous analysis of similar looking deposits showed them to be small particles of pure iron) obtained during welding of a relatively small test piece was considered extremely undesirable. It was decided to make no further attempts to weld in the partial pressure regime. All future work will be performed at hard vacuum (10^{-4} Torr or less).

It was found that variations of beam oscillation (pattern, frequency, and size) affected the size of the fusion zone voids. However, no parameters were developed which eliminated the presence of the fusion zone voids. The pattern which appeared to yield the best results was a circle. Other patterns such as sine wave, square wave, triangular wave, all aligned with and perpendicular to the welding direction were attempted. Welds made without any beam oscillation were miserable failures. The circular pattern seemed to produce welds that during welding minimized the amount of spatter. The frequency used on the oscillated circle was seen to be influential. Figure 8 is a photograph showing welds 28 and 29 made at frequencies of 1000 and 50 hertz respectively. The lower frequency gave superior results and it was also observed that during welding there was less spatter and weld metal agitation. In Figure 9 a comparison can be made between welds #44 and #45. Weld #45 was made at 15 hertz while Weld #44 was made at 200 hertz. Weld #45 appears to be void-free, however, other cross sections revealed the presence of a relatively small void. Again, the lower frequency resulted in a reduction in the size of the void. It was found that 9 hertz appears to be the lower limit on oscillation frequencies. Weld #47 shown in Figure 10 bears witness to this conclusion. From these preliminary results, a circular beam oscillation pattern at a frequency of between 15 and 25 hertz appears to give the best results.

It was also observed that the pattern, size, and frequency of beam deflection did influence the total penetration. A variation by as much as 3/4" of penetration was observed under different beam oscillation conditions. Typically, however, the variation would be of the order of 1/4". This influence on weld penetration is not especially important at this point owing to the large voids encountered. So the primary emphasis was on exploring beam oscillation directed toward eliminating the presence of the voids.

Figure 8. Photomicrograph of an etched cross-section showing partial penetration welds #27, #28, and #29 made in the horizontal welding position. (Photomicrograph shows the effect of beam oscillation frequency on size of voids. Weld #28 made at 1000 hertz, Weld #29 made at 50 hertz.)

Figure 9. Photomacrograph of an etched cross-section showing partial penetration Welds #43, #44, and #45. (Photomacrograph shows the effect of beam oscillation frequency on size of fusion zone voids. The frequencies used were 25 hertz for Weld #43, 200 hertz for Weld #44, and 15 hertz for Weld #45.)

Figure 10. Photomicrograph of an etched cross section showing partial penetration Welds #47, #48, and #49 made in the horizontal welding position. (Photomicrograph shows the result of using a beam oscillation frequency that is too slow. Weld #47 was made at a frequency of 9 hertz and can be compared with the welds made in Figure 9.)

After making 55 welds under different conditions, without successfully eliminating the presence of voids, it became apparent that the electron gun should be tilted (inclined) with respect to the level horizontal position. During welding using an inclined angle, gravity should pull the liquid metal down into the weld cavity and promote better fusion. Experiments were performed using various angles between 1.5° and 15° . Figure 11 is a sketch showing the angled approach taken.

FIGURE 11 SKETCH SHOWING HORIZONTAL ELECTRON BEAM WELDING USING AN ELECTRON BEAM INCLINED WITH RESPECT TO THE LEVEL HORIZONTAL POSITION

Figure 12 shows Weld #71 which was made at 1.5° angle of inclusion. This appears to be the minimum angle for which these large partial penetration welds can be made without the presence of the large voids previously encountered. Figure 13 presents Weld #67 which was made at a 2.5° angle of inclination. The 2.5° angle showed consistent results and also a reduction in the extent of root porosity. Other welds made using angles of 5, 10, and 15° showed no additional beneficial effects from that observed with the 2.5° angle of inclination.

It was decided to use an angle of inclination of 3° for future horizontal position development work. Obviously, only a few degrees is very beneficial with respect to elimination of voids. Although welds were made at 2.5° , it was felt that the added margin of going to 3° would be desirable from a safety and repeatability aspect. Also, if a closed square butt joint preparation were used, it could be fused with a 2.5° electron beam. However, the margin for error is very limited. Therefore, to accommodate gapping and mismatching during fit-up, a $2\text{-}1/2^{\circ}$ beveled joint would be desirable. Since one would thereby use a beveled joint preparation, it was decided to use a 3° angle of inclination for added precaution.

Figure 12. Photomicrograph of an etched cross section showing partial penetration Welds #71, #72, and #73 made in the horizontal welding position. (Weld #71 was made with a 1.5° angle of electron beam inclination with respect to the level horizontal position. Note: 1.5° angle of inclination is the minimum angle needed for elimination of large weld metal voids. Compare Weld #71 with welds shown in previous figures.)

Figure 13. Photomacrograph of an etched cross section showing partial penetration Welds #65, #66, and #67 made in the horizontal welding position. (Weld #67 was made with a 2.5° angle of electron beam inclination with respect to the level horizontal position. Note the absence of the large fusion zone voids using the 2.5° angle of inclination.)

Figure 14 is a sketch illustrating the proposed joint design for an 8" thick plate compatible with a 3° angle of inclination. This weld preparation has disadvantages when compared to the closed square butt weld preparation originally envisioned. However, these disadvantages should be relatively minor and/or insignificant. The disadvantages identified to date are the added cost of machining the beveled joint versus the square joint and the probable additional nondestructive inspection costs. The advantages, on the other hand, are 1) the ability to properly make the electron beam weld which allows the use of the electron beam welding process which should be extremely economically attractive, and 2) reduced tolerance with respect to gapping and mismatching for successful EB welding.

FIGURE 14 SKETCH SHOWING WELD JOINT FOR HORIZONTAL ELECTRON BEAM WELDING WITH A 3° INCLINED ELECTRON BEAM

Several welds were made in an attempt to establish the range of beam oscillation amplitude. The amplitude referred to in the following material is for a circular pattern of beam deflection and the number corresponds to the potentiometer setting. At a later date and upon final development of a welding procedure, the potentiometer setting number will be correlated with an actual circle size on the plate surface. It was found that an amplitude of 25 appears to be the minimum for producing welds free from voids. Figure 15 is a photograph showing Weld #74 which was made with an amplitude of 25 and Weld #75 which was made with an amplitude of 30. The maximum amplitude has been estimated to be a setting of 55. Figure 16 shows Welds #89, #90, and #91 which were made respectively at 50, 55, and 60 amplitude numbers. Not shown in the photograph was a large centerline solidification void appearing in Weld #91. In comparing Weld #90 and #91, it can be seen that Weld #90 (amplitude 55) contains no solidification centerline void or large voids, but does possess transverse fusion zone cracks. Thus, the range in amplitude setting is from 25 to 55. An amplitude of 45 appears to be optimum.

The effect of focus location has not been fully evaluated. Many welds have been made with a focus slightly above the weldment surface. It appeared that this location has produced the best results to date. However, future experimentation will be conducted to more fully identify the optimum focal location.

Initially a gun-to-work distance of 6" was used. Later, an 8" gun-to-work distance was used and appeared to result in a smoother, quieter operation with less spatter. Additional work will be done to more fully identify the gun-to-work distance.

The travel speed has been observed to have a major effect on the cracking encountered in the fusion zone. No heat affected zone cracks have been observed in any of the weldments made to date. As the travel speed is increased to levels much above 5 inches/minute, the weld metal experiences a large centerline solidification crack/void. At a travel speed of 4 inches/minute (ipm) with the conditions used, a few transverse cracks have occurred in the fusion zone generally at the mid-depth region.

Figure 15. Photomacrograph of an etched cross section showing partial penetration Welds #74, #75, and #76. (Weld conditions are identical except for preheat and beam oscillation amplitude. Weld #74 made at an amplitude setting of 25, Weld #75 made at an amplitude setting of 30, and Weld #76 made at an amplitude setting of 35. Too small an oscillation amplitude will result in large weld metal voids as seen in Weld #74).

Figure 16. Photomicrograph of an etched cross section showing partial penetration Welds #89, #90, and #91 made in the horizontal welding position. (Weld conditions identical except Weld #89 made with an oscillation amplitude of 50, Weld #90 made with an oscillation amplitude of 55, and Weld #91 made with an oscillation amplitude of 60. Note presence of undercut associated with Weld #91. Also not shown in the photomicrograph is a large centerline solidification void in Weld #91. The apparent maximum beam oscillation amplitude is a setting of 55. Also note the presence of necklace defects in Welds #89 and #91 and transverse microcracks in the weld metal of #90.)

Figure 17. Photograph of an etched cross section showing partial penetration welds #86, #87, and #88 made in the horizontal welding position. (Welds were made with different focus locations, 4 ipm travel speed, and oscillation amplitude of 45. Although Weld #86 is defect-free in this section, other sections showed transverse fusion zone microcracks and necklace defects similar to those seen in Welds #87 and #88.

Figure 17 shows Weld #86 which was made at 4" minute travel speed with an oscillation amplitude of 45. In the cross section shown, Weld #86 was defect-free. However, other cross sections revealed the presence of a few transverse fusion zone microcracks similar to those seen in Welds #87 and #88 of Figure 17. At 3.75 ipm it was observed that fewer transverse cracks appeared than at 4.0 ipm. These cracks are only observable during etching of the sanded, cross sectioned samples or upon dye penetrant inspection of the cross sectioned samples. Another weld was made using a travel speed of 3.50 ipm. This weld, #94, showed the complete absence of any fusion zone transverse microcracks. In fact, Weld #94 was free of all defects encountered to date except one — presence of a lack of fusion defect at the weld root which resembles and is often called a root crack, taking the outline of the fusion at the weld root. Commonly this is called a necklace defect.

Future experimentation will involve modifications to weld current, travel speed, gun-to-work distance, focal locations, oscillation amplitude, and frequency to determine an appropriate set of welding parameters which will eliminate the necklace defect. Upon elimination of this defect, the goal for developing partial penetration welding procedure in the horizontal position will be satisfied.

Summary

95 welds have been made to date in an attempt to develop a non-defective 4-1/2" deep partial penetration electron beam welding procedure on SA 387 Grade 22 Class 2. Experimental welds were made on 6" thick plate material. These welds were cross sectioned and the results observed. Modifications of the welding procedure were made and the process of sectioning and observing the weld repeated.

Initially it was observed that, when welding in the horizontal position, liquid metal would drain from the fusion zone which resulted in the formation of a large void in the weld. This drainage was counteracted by attaching a shelf to the plate surface to support the liquid metal. Although the use of a shelf was effective at reducing the size of the fusion zone void, it was not sufficient to eliminate this defect. In later attempts, it was observed that the size of the fusion zone voids was strongly influenced by the conditions of beam oscillation; amplitude, frequency, and pattern. However, no combination of welding parameters were developed

which eliminated the presence of these voids. Experimental welds were then made where the electron beam was inclined with respect to the level horizontal position. It was found that by inclining the electron beam at an angle of 3° with respect to the level of horizontal position that no fusion zone voids occurred. Thus, the presence of large fusion zone voids was overcome by 1) use of a shelf, and 2) inclining the electron beam at an angle of 3° with respect to the level horizontal position.

Welds were made at pressures of between 25 and 100 microns. No beneficial effects were observed and contrarily an excessive sooty deposit was produced and erratic equipment operation was encountered. All future work will be done using hard vacuum conditions.

Other defects have been encountered and most of which have been successfully eliminated. It was observed that fusion zone centerline solidification voids occurred with travel speeds in excess of 5 ipm. Root pores and centerline solidification voids were eliminated by using a circular beam deflection with an appropriate amplitude (the range on the amplitude appears to be between amplitude pot setting numbers 25 and 55). It was also observed that the best results were obtained by using lower frequencies of beam oscillation. It appears that the optimum frequency is 15-25 hertz. With this, welds were made and cross sectioned and appeared to be defect-free. However, upon belt sanding and etching or dye penetrant inspection, either transverse fusion zone microcracking or root cracking (referred to as a necklace defect) was observed. It was found that fusion zone transverse microcracking was eliminated by reducing the travel speed to 3.5 ipm. The presence of the necklace defect has not yet been eliminated. Of the 95 welds examined to date, there have been no observations of any heat affected zone cracks or fissures.

Work will continue during the next quarter to develop a non-defective partial penetration welding procedure in the horizontal position. Upon completion of this development, a partial penetration weld procedure will be developed for welding in the vertical position.

Step 8 — Demagnetization Procedure Development

Past work resulted in the development of a magnetic shield which is sufficient to protect the electron beam from magnetic field strengths of up to 40 gauss. It was computed that the use of this shield would only be necessary if a 1 gauss magnetic field existed between the plate surface and the electron gun. It was decided to measure the field strength between the electron gun and the plate surfaces for the remainder of this project as the various plates are used. In that regard, a log has been established for recording measurements taken. Two measurements are being recorded. Using a magnetic field indicator, the weld samples are scanned prior to welding to determine the maximum field strength anywhere around the block. Typically, the maximum field strength has appeared at a corner of the block and the maximum strength measured to date is 10 gauss. Also, the maximum field strength existing between the plate surface and the electron gun has been measured and recorded. To date, the maximum field strength measured is 1 gauss. This field exists only for approximately 1 inch above the plate surface. From 2 inches and out, the maximum magnetic field strength measured to date is zero gauss. Thus, the results to date indicate that the use of the magnetic shield may not be necessary and hence no precautions will be needed for proper joint fusion when working with this magnetic material.

Step 12 — Quarterly Reports

The second 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

Complete.

Step 2 - Material Procurement

Complete.

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 welds, 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 is nearly complete for the development of the welding procedure in the horizontal position. Thus, the final weld procedure should be established during the next quarter. Work will then concentrate on developing the required welding procedures in the vertical welding position. This work should be completed so that by the end of the next quarter, partial penetration welding procedures should be developed for both the horizontal and vertical welding positions.

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 this project, magnetic field measurements will be made on the pieces being welded to determine the strength of the field between the electron beam 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 strength 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 on 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 third quarterly report will be issued.

Step 13 — Final Report

No work planned.