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

Fourth Quarterly Report for the
Period 1 July 1978 — 30 September 1978

Prepared By

MASTER

Charles M. Weber

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Work Performed Under Contract EF-77-C-01-2606

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Division of Fossil Energy
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ABSTRACT

This report is the fourth 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 July-September 1978. Due to the late arrival of the steel to be used in this project, a six month extension in the completion date has been made. Work is in progress for developing 4-1/2" deep partial penetration electron beam welding procedures. A total of 257 welds have been made to date. Several defects have been encountered and successfully eliminated. The occurrence of a necklace defect, which has been shown to be a cold shut resulting from improper solidification, has not yet been eliminated. It has been observed that the beam oscillation pattern is influential on the behavior of the weld cavity during welding. In the vertical welding position, it has been determined that the use of a welding shoe is required.

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 October 31, 1978

Step 1 – Planning

Complete.

Due to the late arrival of the steel required for this project, a six month, no cost extension of this contract has been made.

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. This material has been certified by the vendor to conform to the requirements of SA 387 Grade 22 Class 2.

Step 3 – Partial Penetration Procedure Development

A total of 257 partial penetration electron beam welds have been made to date. Examination of the experimental welds has shown that a necklace defect is usually present. This defect was shown to be a cold shut resulting from improper solidification. Attempts to eliminate this condition by modifying the welding procedure have, to date, not been completely successful. Four defect-free welds have been made, but the conditions are apparently not stable as repeatable results were not obtained.

It has been learned that the beam oscillation conditions (pattern, frequency, and amplitude), are very influential on the occurrence of defects. Numerous patterns have been attempted, each producing different results. The optimum welding conditions that reproducibly yield defect-free welds have not yet been developed.

Welds made in the vertical position have been accompanied by a small amount of liquid drainage from the molten pool. This will necessitate the use of a welding shoe which is presently being built.

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 third 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 ERDA 535
(2/1/77)

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

PAGE 1 OF 1

CRD 1013

1. Contract Identification Electron Beam Welding - Field Fabrication of 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 P.O. Box 835, Alliance, Ohio 44601				5. Contract Start Date 19 September 1977																					
				6. Contract Completion Date 19 September 1979																					
Step	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months												10. Percent Complete											
		1st Qtr.	J	F	M	A	M	J	J	A	S	O	N		D	J	F	M	A	M	J	J	A	S	O
1	Planning																								
2	Material Procurement																								
3	Partial Penetration																								
4	Vacuum Level																								
5	Full Thickness																								
6	Start/Stop																								
7	Arc-Out																								
8	Demagnetization																								
9	Fit-Up																								
10	Laboratory Demonstration																								
11	Mechanical Properties																								
12	Quarterly Reports																								
13	Final Report																								
11. Remarks First rescheduling July 17, 1978																									
12. Signature of Contractor's Project Manager and Date Frank L. Hovanec <i>F. L. Hovanec</i> 7-19-78												13. Signature of Government Technical Representative and Date													

3.0 DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Step 1 – Planning

Complete.

Due to the late arrival of the material required for this project, it was necessary to request a six month, no cost extension of this contract. This extension has been approved and implemented.

Step 2 – Material Procurement

Complete.

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 two-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 (approximately 4-1/2" deep) at three vacuum levels (approximately 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 welding procedures. During this reporting period work was performed to develop a partial penetration procedure in the horizontal and vertical welding positions. This report presents the results of this effort to date.

Results & Discussion

As mentioned, a trial and error experimental approach is employed to develop the welding procedures. Many difficulties have been encountered in attempts to make acceptable welds. Nearly all these difficulties have been

satisfactorily resolved. However, the repeatable production of defect-free welds has not been accomplished to date. The presence of a necklace defect has been the only remaining obstacle. In examining the welds, the technique that has been used is to extract several (e.g., six) cross section samples which are then dye penetrant inspected. This approach has been necessary since the existence of the necklace defect (which is usually extremely small) may or may not be revealed by visual observation of the cross section.

To date, 257 experimental welds have been made. The vast majority of these welds were made in the horizontal welding position.

Horizontal Position

Several different types of defects have been encountered in this project, and much has been learned about appropriate corrective actions which can be made to the welding procedure to eliminate the defects.

Voids

Large voids and/or holes in the fusion zone can be eliminated by the use of a shelf attached to the surface of the sample and by tilting the electron gun on a small angle, such as 3° .

Centerline Solidification Voids

Centerline solidification voids have been encountered when the weld width is too large, the travel speed too high, or the weld shape contains bulges. Welding speeds in excess of 5 ipm have given rise to centerline solidification voids. When conditions are used that produce a weld with a parallel sided profile and a weld width which is not too large, this defect can be avoided. The location of beam focus will influence the shape of the fusion zone; the travel speed and oscillation amplitude will influence the fusion zone width. There is flexibility with these welding parameters and the presence of solidification voids can be rather easily eliminated.

Transverse Fusion Zone Microcracking

Some welds have been observed to contain transverse fusion zone microcracking. These are small cracks occurring in the fusion zone perpendicular to the penetration. It has been learned that excessively wide welds are likely to contain this condition. As oscillation amplitude setting of 50 or greater will give rise to this condition. In some cases, a travel speed in excess of 4 ipm was observed to promote this transverse cracking.

Root Porosity

The presence of root pores is primarily influenced by the beam oscillation conditions (pattern, frequency, and amplitude) and secondarily by focus location. An oscillation amplitude setting of greater than 30 has been effective in reducing root porosity (the apparent optimum amplitude setting appears to be an amplitude setting of 35-40). The frequency of the oscillation should be kept low. It was found that a frequency of 25 hertz appears to be optimum. The pattern of beam oscillation has been seen to be very influential on the results of welding and more will be said about this later. There appears to be considerable latitude on the location of beam focus with regards to root porosity formation. Welds have been made with focus settings from 6" below the surface to 2" above the surface. In general, as the focus goes deeper into the material, the penetration will increase slightly and there will be an increased tendency toward root porosity. For this and other reasons to be mentioned later, it appears that the optimum focus is slightly above plate surface. In all, root pores can be controlled with the appropriate beam oscillation conditions and focal location.

Necklace

Thus, solutions, or appropriate welding procedures, have been determined which will eliminate all but one of the defects observed. The remaining defect is the necklace defect. For illustration, Figure 2 is a cross section of weld #120 which shows a necklace defect. The necklace defect given in this figure is larger than most that have been observed. Usually one must examine several cross sections using dye penetrant inspection to determine whether or not the weld possesses a necklace defect.

Figure 2. Photograph of an etched cross section showing partial penetration welds #120 and #121. (A necklace defect is seen in the root of Weld #120)

The presence and extent of the necklace has been observed to be correlated with the shape of the weld root. Welds that are extremely pointed or spike-like in nature have been observed to nearly always contain a necklace defect. Whereas welds with a well-rounded root often do not exhibit the necklace defect. A trial and error experimental procedure has been used to attempt to optimize the weld parameters, with emphasis on producing welds where the shape of the weld root is given major importance.

It appears that "soft" beam conditions promote well rounded roots. Welds were made with various gun-to-work distances between 6 and 10". More rounded roots were obtained with the larger gun-to-work distances. Also the amount of spatter coming from the weld zone during welding was reduced with the larger gun-to-work distances. A 9" gun-to-work distance yielded the best results and that distance has been selected as optimum.

The location of beam focus has been varied from 6" below surface to 2" above the surface. Changes in focus will influence the weld shape and the total penetration. One should set the focus to obtain a reasonably parallel sided weld. When focusing deep into the material, a more Vee-shaped weld is obtained and in the associated sharp root, necklace defects and perhaps root pores are very common. Focusing too much above the plate surface will produce welds with a convex shape and if a sufficient fusion zone width is obtained in the convex region (bulge), then either transverse fusion zone microcracking or centerline solidification voids will result. It has been determined that for a 9" gun-to-work distance that a focus slightly above plate surface yields the best results.

It was thought that perhaps the restraint encountered during welding on solid blocks could be responsible for the presence of the necklace. The welding of a joint would impose less restraint than the welding of a solid block. Consequently, 8" thick joints were machined and welded. However, examination of the welded joints showed the presence of the necklace defects just as they were seen in the solid blocks.

It has been determined that the beam oscillation conditions used are very influential on metal flow, cavity operation, spatter, and certain weld defects. Figure 3 provides an illustration of some of the beam oscillation patterns employed. Each of these patterns has been observed to affect the metal flow, spatter, and presence of defects.

Figure 3. Illustration of Beam Oscillation Patterns Used

To illustrate the significant difference on cavity behavior using different patterns, Figures 4 and 5 are included. Here welding was abruptly terminated and the samples were sectioned at the location where welding was terminated. In Figure 4 a circular pattern of beam oscillation was used. From this figure, we can see that the metal at certain locations is washing in to close the cavity. Close examination also shows that the weld root has solidified first and that a necklace defect is present. In Figure 5, a different pattern of beam oscillation was used. Here a circular pattern was used and periodically the trailing half of the circle's amplitude was larger. A marked difference is seen in comparison with Figure 4 in that the weld cavity is open for the entire length. Thus, it can be seen that the beam pattern is most influential. With each pattern attempted a slightly different response has been obtained. It must be evident that the possibilities are rather staggering. Any pattern that can be envisioned can be electronically produced and can be expected to yield a different result.

Figure 4. Photograph of an etched cross section showing the weld cavity appearance when welding is abruptly terminated. (Note the metal flow in the cavity, especially the areas where the cavity is closed. A circular beam oscillation pattern was used.)

Figure 5. Photograph of an etched cross section showing the weld cavity when welding is abruptly terminated. (Note the metal flow in the cavity, especially how the cavity is open the entire length. A circular beam oscillation pattern was used where periodically the trailing half of the circular amplitude was larger.)

To further assist the understanding of the necklace defect, a scanning electron microscope was used for examination. Figure 6 presents a 21X view of a rather large necklace. Although the defect appeared to be on the fusion line, examination of this necklace showed that it was not. The defect is slightly inside the fusion line, meaning that molten metal did extend beyond the necklace. Analysis within the necklace and in the vicinity of the necklace defect showed 1) normal inclusion content, 2) no segregation, 3) no unusual chemistry. Photographs of the surface of the necklace were made. Figure 7 is such a photograph giving a 630X view. Observation of the dimpled pattern of this surface showed that it was a freely solidified surface. This was not a crack or has not been fractured but simply there was not enough metal present during solidification to yield a completely solid weld. This defect is a cold shut. The relatively rapid solidification of the metal in this region of the weld has resulted in a cold shut.

With this information, it was felt that preheat could be used to reduce the solidification rate. Welds were made with preheats varying from room temperature to 700⁰F. Examination of these welds showed the presence of the necklace defect and hence it was concluded that the preheats used were not sufficient to substantially reduce the solidification rate and hence the necklace defect was still observed.

Since preheat did not provide a sufficient reduction in the solidification rate, welds are now being made with a substantially reduced travel speed. This experimentation is now in progress.

Of the 257 welds made to date, there were four that have been defect-free. These four welds were made using different procedures and attempts to repeat the results were not successful. This apparently means that it is possible to make a defect-free weld in this material at this thickness, since it has been done, but the conditions used to date are not stable.

Of the 257 welds made to date, there has been no observation of any heat affected zone cracks or fissures.

Figure 6. Photograph at 21X of a rather large necklace defect

Figure 7. Photograph taken with scanning electron microscope at 630X showing a surface of a necklace. (This surface is a freely solidified surface which shows that the necklace defect is a cold shut.)

Vertical Welding Position

Approximately 15 welds have been made in the vertical welding position. It was quickly learned that welding in the vertical up direction is much preferred to welding in the vertical down direction. Welding vertical down results in an excessive amount of weld spatter and drainage from the molten pool. Apparently the beam does not provide enough support to keep the liquid in position. Welding in the vertical up position is seen to be reasonably stable and is accompanied by only a small amount of liquid loss. Attempts were made to counteract this liquid loss by inclining the beam upwards with respect to the normal position. Welds were made with angles varying between 0 and 20 degrees. No significant difference was encountered and even at 20 degrees gravity was not sufficient to keep the liquid contained in the molten pool. It has thus been determined that the use of a shoe is necessary for containing material loss when welding in the vertical position. Such a shoe is presently being fabricated.

Summary

257 welds have been made to date in attempts to develop a non-defective 4-1/2" deep partial penetration electron beam welding procedure on SA 387 Grade 22, Class 2 in the horizontal and vertical positions. Many defects have been encountered and overcome. The presence of a necklace defect has been observed by dye penetrant inspection of cross sections. Scanning electron microscope analysis shows the defect to be a cold shut resulting from improper solidification.

Some of the welding parameters have been optimized. Those parameters that have been optimized are as follows: a 9" gun-to-work distance, a focus slightly above the sample surface, an oscillation amplitude setting of from 35 to 40, a frequency of about 25 hertz. It has been observed that the oscillation pattern is very influential on the weld metal flow, cavity operation, presence of defects, and generation of spatter. Numerous patterns have been attempted, but no condition has yet been obtained which eliminates the formation of the necklace defect.

Trial welds made in the vertical welding position have shown that the use of a welding shoe to contain the liquid metal is necessary. Welding in the vertical up direction is much preferred to welding in the vertical down direction. Tipping the electron beam uphill from normal to the sample surface did not eliminate liquid drainage from molten pool for angles up to 20° .

Of the 257 welds examined to date, there has been no observation of any heat affected zone cracks or fissures.

Work will continue during the next quarter to develop non-defective partial penetration procedures for both the horizontal and vertical positions at the various vacuum levels. Modifications to the welding procedure which are anticipated to affect the solidification at the weld root will be attempted and a determination made as to whether these modifications are successful at eliminating the necklace defect.

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 and 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 third 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 and 8" thick SA 387 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 procedure will be used for each of the three vacuum levels of interest (0.06, 40, and 100 microns). This process is nearly complete for the development of a welding procedure in the horizontal position. In the vertical position, a welding shoe will be constructed and the same experimental technique will be used to establish a vertical welding procedure. 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.

Step 4 — Selection of Vacuum Level

In Step 3 trials will be made using various vacuum pressures. For each welding position from the results obtained in Step 3, a welding procedure will be selected that gives the most consistent and reliable results at the highest pressure.

Step 5 — Full Thickness Procedure Development

Using the procedures developed in Steps 3 and 4, trial, bead-on-plate welds will be made on 8" thick SA 387 Grade 22 Class 2 material. The full 8" thickness will be welded (one partial penetration weld from each side). These welds will be non-destructively examined and cross sectioned. If necessary, modifications to the welding procedure will be made such that acceptable 8" thick welds are produced.

Steps 6-7

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 fourth quarterly report will be issued.

Step 13 — Final Report

No work planned.