

P-No. 4 and P-No. 5A Temperbead Repair Using the Flux-Cored Arc Welding (FCAW) Process



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Technical Report

P-No. 4 and P-No. 5A Temperbead Repair Using the Flux-Cored Arc Welding (FCAW) Process

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Final Report, June 2001

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REPORT SUMMARY

Over the past several years, EPRI has sponsored research to study an enhanced weld overlay repair method that would be applicable in lieu of reducing operating pressure and output when damage occurs in a main steam or hot reheat piping long seam weld. Project investigators believed that, with recent process and filler material advances, flux-cored arc welding (FCAW) could be used for the necessary high deposition temperbead weld. This report outlines the development of the temperbead welding approach and includes supporting data from research tests.

Background

In 1995, the National Board Inspection Code (NBIC) for the first time permitted the use of temperbead welding repair methods to address carbon and low alloy steel components. Since then, several improvements to the Code have been implemented that enable utilities to more readily take advantage of the repair methods. An additional Code revision, requested by several utilities, would permit the use of a higher deposition process, FCAW, for temperbead welding repair applications.

Objectives

- To provide test data and the basis for revisions to the NBIC RD-1000, Welding Method 4, thus supporting the use of the FCAW process for temperbead welding applications
- To assist in securing acceptance of the FCAW process for temperbead welding applications, thus permitting its use for long seam piping weld overlay applications

Approach

Investigators reviewed the literature to locate research or development efforts for which FCAW temperbead parameters had been developed. Unfortunately, the majority of temperbead research and procedures have focused on two primary welding processes, gas tungsten arc and shielded metal arc. EPRI, however, has developed and demonstrated at least six FCAW temperbead repair procedures over the past four to five years. These procedures are summarized in this report, and a repair methodology is provided to support revisions within NBIC RD-1000.

Results

Six temperbead repair applications have been thoroughly reviewed and include tensile, bend, hardness, and toughness data. The temperbead procedures have been applied to developmental coupons as well as to two full-size mockup components. In each case, superior heat-affected zone (HAZ) properties have been developed. Additionally, at least two FCAW filler metals have been identified for use in the non-postweld heat-treated condition. Specific controls for the FCAW process have also been identified and can readily be implemented into the NBIC repair practices upon NBIC approval.

EPRI Perspective

In 1999, the Fossil Repair Applications Center (FRAC) embarked upon a program to develop an alternative to de-rating a plant's output when damage is located in a main steam or hot reheat piping long seam weld. The alternative employs the use of a weld overlay along the length of the long seam weld and restores the structural integrity of the piping component. The repair method can be used in lieu of reducing operating pressure and output. EPRI report TE-114212 extensively reviews the developmental effort of this repair.

To make the repair technology cost-effective, a higher deposition repair process and practice was warranted. Recent advances in the FCAW process and in filler materials led investigators to believe that the FCAW process could be readily adapted to high deposition temperbead welding. This report highlights the development of the temperbead welding approach and provides supporting data to be provided to NBIC.

Keywords

Temperbead welding

Welding

Repair

Low alloy steels

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INTRODUCTION

Between 1993 and 1996, under the sponsorship of 21 utility members, EPRI spearheaded a research effort (RP3484-01) to compare temperbead and postweld treated repair weldments for various fossil components including main steam and hot reheat piping, headers, and turbine casings. The program conclusively demonstrated that shielded metal arc welding (SMAW) temperbead repairs (employing controlled deposition practices without postweld heat treatment [PWHT]) produce comparable or improved remaining life than welds with PWHT [1-6].

Other organizations, including the Pressure Vessel Research Council, Edison Welding Institute, Ontario Hydro, and Pacific Gas & Electric have performed successful qualifications of temperbead welding utilizing the SMAW process. Many of these were recently highlighted in Welding Research Council Bulletin 412 [6,7].

In parallel to the research conducted by these organizations and by EPRI, the National Board Inspection Code elected to incorporate temperbead welding of carbon and low alloy steels into the 1995 Edition of NBIC RD-1000, “Welding Methods as Alternatives To Postweld Heat Treatment,” under Welding Method 2. Utilities and other users viewed this as a very positive step in that an alternative to high temperature postweld heat treatment was finally available for CrMo piping and header applications. Even so, concern was expressed by utilities over the notch toughness requirements found in the 1995 Edition. Most utility piping was ordered without notch toughness requirements.

After several inquiries by utilities regarding the use of RD-1040 Welding Method 2 on originally installed materials without notch toughness requirements, NBIC revised RD-1000 to incorporate four separate welding methods [8,9] (see Appendix A). The 1995 edition included three welding methods, whereas the 1998 edition now includes four methods. Welding Method 4 was added to address use in power boiler applications where rules of the original code of construction did not require notch toughness testing. Welding Method 4 was specifically limited to P-No.4, Groups 1 and 2 and P-No. 5A steels as permitted for welded construction by the applicable rules of the original code of construction. Furthermore, Method 4 was limited solely to applications involving the SMAW process using low hydrogen electrodes.

In contrast, Welding Method 2 should be used when the original code of construction requires notch toughness testing. P-No. 4 and P-No. 5A materials (along with several others) were included under this method. The method also permits the use of several welding processes including SMAW, gas metal arc welding (GMAW), flux-cored arc welding (FCAW), and gas tungsten arc welding (GTAW), and it requires toughness testing.

Introduction

As with any other Code, RD-1000 continues to undergo revisions and additions. The 2000 addenda will incorporate a few changes for both Welding Methods 2 and 4. Unfortunately, the changes under Welding Method 4 will not incorporate the addition of the FCAW process. *The following discussion and presentation of test results will provide the basis for revisions to Welding Method 4 that incorporate the FCAW process.*

2

FCAW TEMPERBEAD WELDING DEVELOPMENT

2.1 Temperbead Pipe Welds CO-2 and CO-4

In 1996, EPRI initiated a project under its Strategic Science & Technology group to investigate the use of FCAW for welding piping without postweld heat treatment. The project was an extrapolation of the work performed under the successful Weld Repair of High Temperature-High Pressure Components program, under which SMAW welds were evaluated in both the PWHT and temperbead welded conditions. The current FCAW project utilizes the tempering methods that were used in the earlier program.

Under this effort, four weldments were performed with and without postweld heat treatment. Only two of those weldments in the non-postweld heat-treated (temperbead) results are described herein.

2.1.1 Weldment CO-2

The first temperbead weldment labeled CO-2 was performed on a 20-inch (50.80 cm) diameter, Schedule 80 (1 inch (2.54 cm) wall) 2-1/4Cr-1Mo (P5A) pipe section. The pipe was beveled with a typical 37-1/2 inch (95.25 cm) bevel, wrapped with heater mats, and preheated to 450F (232C) in the 5G welding position. Root welding was performed using the GTAW process and a Techalloy 1/8-inch (0.32-cm) diameter ER70S2 wire.

FCAW welding of the pipe employed a 0.045-inch (0.114-cm) diameter McKay Speedalloy 91B3-V wire and a 75Ar-25CO₂ shielding gas with a flow rate of 40 CFH (1.13 CMH). Stringer bead welds were used to butter one side of the weldment. A two-layer approach was employed in the 5G welding position. Once the temperbead layers were applied, the remainder of the fill passes were completed (Figure 2-1). All welding consisted of the double up welding approach and used the EPRI/Magnatech co-developed Pipeliner II welding system. The remainder of the fill passes was accomplished using a minor oscillation of 0.180-0.320 inches (4.6-8.1 mm)¹ (average of 1/4 inch [6.3 mm]). A total of seven layers with 17 passes were employed to complete the weld. Cap welding was also accomplished with a minor oscillation of 0.150-inch (0.381-cm) requiring a total of four weld beads. Welding parameters for the two temperbead layers, the fill and cap passes are provided in Table 2-1. A 600F (316C) welding interpass temperature was used throughout the entire welding process.

¹ The minor oscillation provided stability to the arc, while closely simulating stringer-type beads.

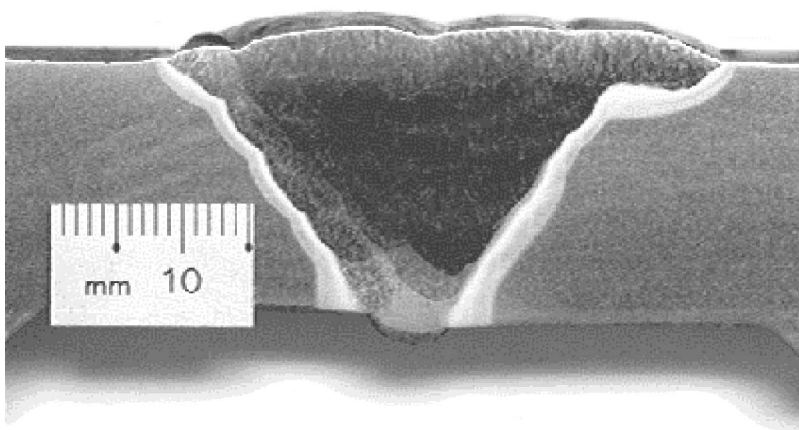


Figure 2-1
A Cross-Sectional View of Weldment CO-2. (Note one side of the weld was buttered using a temperbead approach.)

Table 2-1
Welding Parameters for Weldment CO-2

Weldment CO-2	Two Temperbead Weld Layers	Fill Passes	Cap Passes
Amperage (A)	105	170	170
Voltage (V)	21.3	24.3	24.3
Wire Feed Speed (in/min)	180 (76.2 mm/s)	320 (135.5 mm/s)	275 (116.5 mm/s)
Travel Speed (in/min)	14.0 (5.93 mm/s)	8.0 (3.38 mm/s)	10.0 (4.23 mm/s)
Power Ratio (kw/in ²)	109.4 (16.96 kw/cm ²)	64.9 (10.06 kw/cm ²)	N/A

Upon completion of the weldment, it was postweld baked at 550F (288C) for four hours and then allowed to cool to room temperature. The weldment was sectioned for bends, tensiles, and microhardness testing. Tensile results are shown in Table 2-2. As shown, the weldment exhibited good strength (72,550 psi (500 MPa) average) and was shown to rupture in the base metal away from the weld or heat-affected zone (HAZ). Both of the two side bend tests passed.

Table 2-2
Tensile and Bend Test Results

	Diameter (in)	Area (sq in)	Ultimate Load (lbs)	Ultimate Stress (psi)	Location of Rupture/Type of Failure
Specimen 1	0.502 (1.275 cm)	0.1979 (1.277 sq cm)	14,320 (31,570 kg)	72,400 (499 MPa)	Base/Ductile
Specimen 2	0.498 (1.265 cm)	0.1948 (1.257 sq cm)	14,160 (31,217 kg)	72,700 (501 MPa)	Base/Ductile

Microhardness tests were also performed at four locations (two on each side of the weld). Maximum hardness values at the weld fusion line were shown to be in approximately the 280-300 Hv range (Figure 2-2). It is interesting to note that no apparent improvement in hardness was demonstrated when the buttered side of the weld was compared to the as-welded side of the weldment.

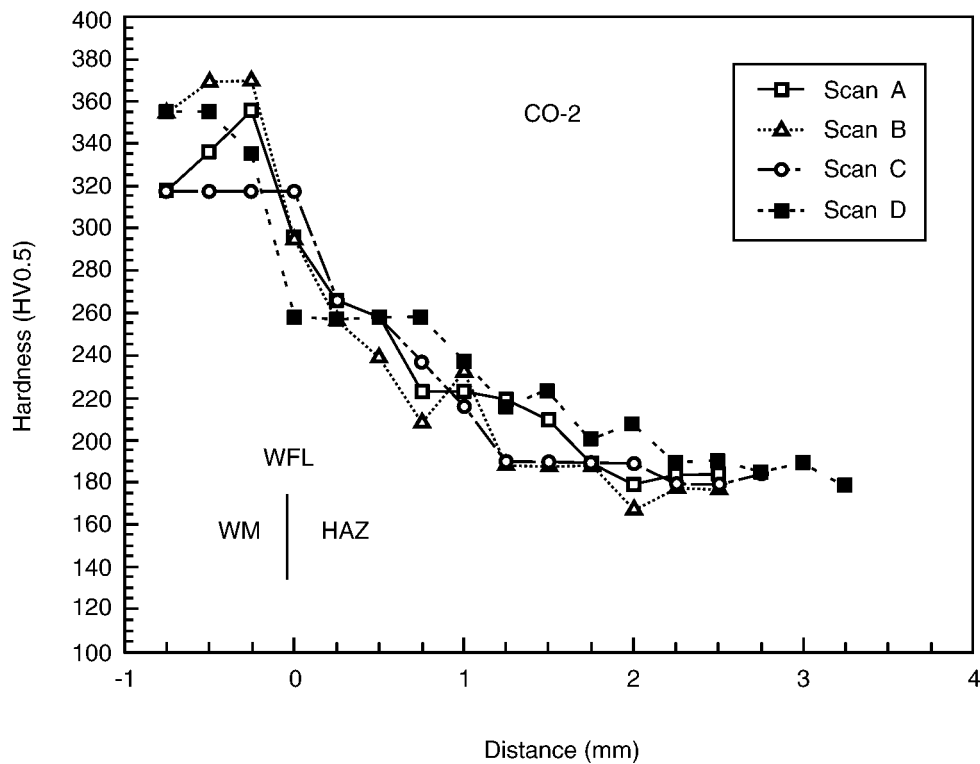


Figure 2-2
Microhardness Plot for Weldment CO-2

2.1.2 Weldment CO-4

A second temperbead weld, CO-4, was performed on a 28-inch (71-cm) diameter 2-1/4Cr-1Mo pipe section that was removed after 100,000+ hours of service from TVA's Gallatin Unit 3. An excavation of a service-removed weldment around roughly one-half of the pipe diameter (Figure 2-3) was performed prior to the temperbead repair. The excavation was approximately 2-1/2 inches (6.35 cm) in width with steep 10-degree sidewalls. The actual depth of the excavation was approximately 0.82 inches (2.08 cm) with 3/16-inch (0.48-cm) of the wall remaining at the inside diameter (ID) surface location. The temperbead repair weld was performed in the 5G welding position and again used the double-up welding approach. The preheat, weld interpass temperature, shielding gas, and filler wire employed were the same as used in the earlier CO-2 weldment.

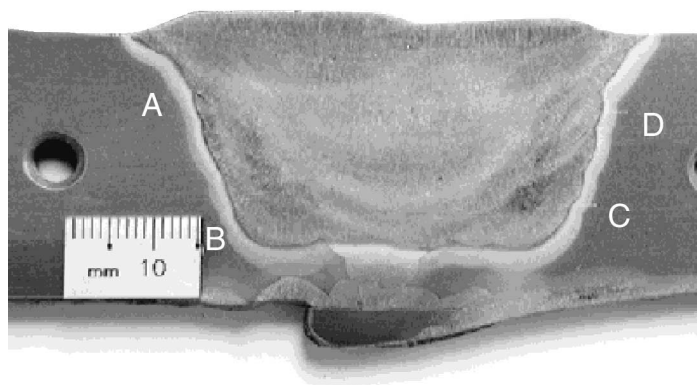


Figure 2-3
Weld Repair CO-4

Welding parameters for the three sidewall temperbead-, fill-, and cap passes are shown in Table 2-3. A slightly different approach to that used for CO-2 was employed for Weldment CO-4. A three-layer stringer-type weld buildup was performed on each 10-degree side wall prior to performing the fill passes. Oscillation throughout the fill passes ranged from 0.960 to 0.999 inches (24.4 mm to 25.4 mm).

Table 2-3
Welding Parameters for Weldment CO-4

Weldment CO-4	Three Temperbead Passes	Fill Passes	Cap Passes
Amperage (A)	160	180	170
Voltage (V)	230	24.6	24.3
Wire Feed Speed (in/min)	245 (103.6 mm/s)	345 (146.0 mm/s)	260 (110 mm/s)
Travel Speed (in/min)	15.0 (6.35 mm/s)	6.0 (2.53 mm/s)	10.0 (4.23 mm/s)
Power Ratio (kw/in ²)	141.7 (21.9 kw/cm ²)	48.4 (7.5 kw/cm ²)	N/A

Mechanical testing of the CO-4 temperbead repair included tensile (at room temperature and 1050F [566C]), bend, microhardness, and toughness tests. Tensile results are provided in Table 2-4 for the service-removed base metal (CO4BM-X), the service-removed weldment (CO4SR-X), and temperbead weld repair (CO4WR-X). Bend tests performed for the repair weldment were also shown to be successful. Microhardness test results are shown in Figure 2-4. Note that the maximum hardness observed in the HAZ adjacent to the weld fusion line was approximately 280 Hv.

Table 2-4
Tensile Test Results for Weldment CO-4

Tensile Properties for CO-4
Base Metal, Service-Removed, and Weld-Repaired Conditions

Spec. ID	Test Temperature (F)	0.2% Yield Strength, ksi*	Ultimate Tensile Strength, ksi*	% Elongation in 1 inch**	% Reduction of Area
CO4BM-1	R.T.	28.8	61.0	31.4	71.7
CO4BM-2	R.T.	29.7	60.7	31.6	71.3
Average		29.3	60.9	31.5	71.5
CO4BM-3	1050 (566C)	19.6	31.9	38.9	77.1
CO4BM-4	1050 (566C)	20.4	32.4	34.3	78.5
Average		20.0	32.2	36.6	77.8
CO4SR-1	R.T.	32.0	62.8	22.2	71.7
CO4SR-2	R.T.	26.3	59.3	51.4	73.0
Average		29.2	61.1	21.8	72.4
CO4SR-3	1050 (566C)	19.2	32.6	23.8	75.9
CO4SR-4	1050 (566C)	17.6	32.7	22.7	73.5
Average		18.4	32.7	23.3	74.7
CO4WR-1	R.T.	36.5	63.5	21.4	68.2
CO4WR-2	R.T.	38.9	65.0	20.8	72.5
Average		37.7	64.3	21.1	70.4
CO4WR-3	1050 (566C)	22.9	33.0	23.6	77.3
CO4WR-4	1050 (566C)	23.4	33.6	23.2	75.4
Average		23.2	33.3	23.4	76.4

*To convert ksi to MPa, multiply the unit by 6.895.

**To convert inches to centimeters, multiply the unit by 2.54.

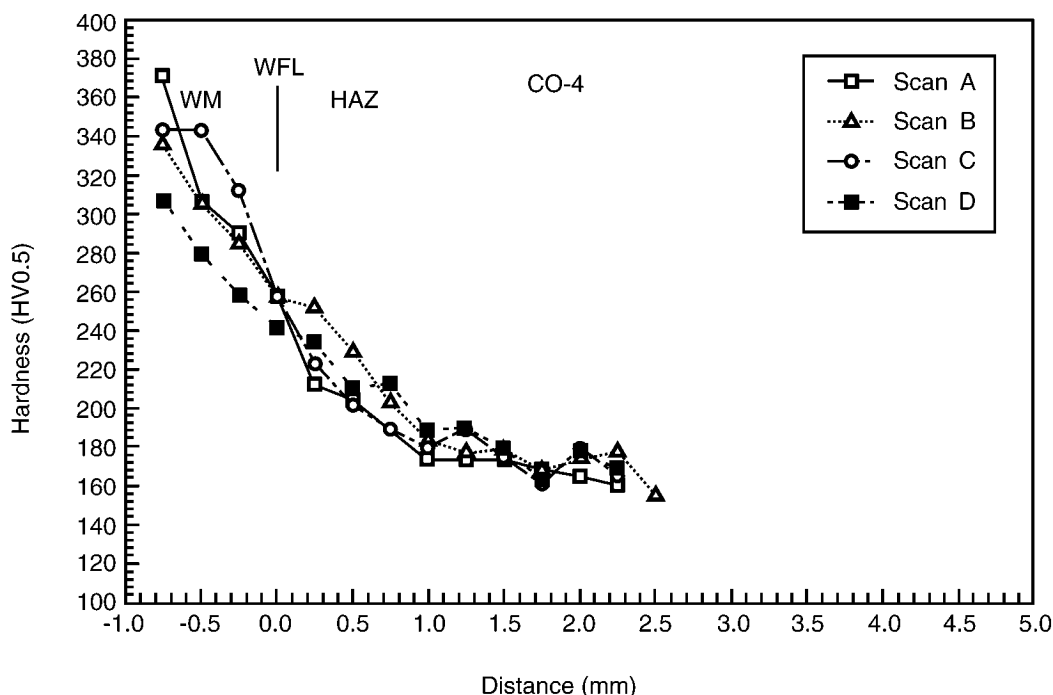


Figure 2-4

Microhardness (Vickers-500g) Scans of the Repair Weld HAZ. (Note the maximum hardness at the weld fusion line is approximately 275 Hv.)

Room temperature Charpy impact tests were performed for the base metal, the service removed weld metal, the new all weld metal repair, and within the heat affected zone for the weld repair. The results are reported in Table 2-5. Comparison of the impact strength suggests the service-removed base metal (60.2 ft-lbs [81.6 N-m]) and HAZ (79.2 ft-lbs [107.4 N-m]) properties exceed the base metal (30.0 ft-lbs [40.7 N-m]). For the repair, the HAZ (68.2 ft-lbs [92.5 N-m]) properties easily exceeded the base metal (30.0 ft-lbs [40.7 N-m]); however, the all weld metal toughness was somewhat inferior. The all weld metal toughness was measured at 16.5 ft-lbs. (22.4 N-m). The lower than expected values were attributed to the fact that the FCAW wire was formulated for use in the PWHT condition, not in an as-deposited condition.

Table 2-5
Charpy Impact Toughness Results for Weldment CO-4

Weldment	Average* Charpy Impact (ft-lbs)	Average* % Shear	Average Lateral Expansion (mils)
<i>Base Metal</i>			
CO4BM	30.0 (40.7 N-m)	35.0	36.1 (0.92 mm)
CO4BM	30.0 (40.7 N-m)	35.0	36.1 (0.92 mm)
<i>All Weld Metal</i>			
CO4SR	60.2 (81.6 N-m)	40.0	56.6 (1.43 mm)
CO4WR	16.5 (22.4 N-m)	11.0	12.8 (0.33 mm)
<i>HAZ</i>			
CO4SR	79.2 (107.4 N-m)	50.0	73.6 (1.87 mm)
CO4WR	68.2 (92.5 N-m)	70.0	62.0 (1.56 mm)

* Average of three tests

2.2 P-No. 5A Seam Weld Overlay Welding—Development Coupons

Between 1999 and 2000, EPRI initiated a program targeted at “Weld Overlays to Extend the Useful Life of Seam Welded High Energy Piping.” A portion of the program focused on the development of weld overlay technology for P-No. 4/P-No. 5A materials. As part of this effort, two one-half diameter temperbead weld overlays were applied to a 20-inch (50.8-cm) diameter (1-1/8 inch (2.86 cm) thick) 2-1/4Cr-1Mo pipe section (Figure 2-5). The first weld overlay was applied using the stringer bead approach, while the second employed a minimal weave (<1/4-inch [0.64-cm]) oscillation approach.

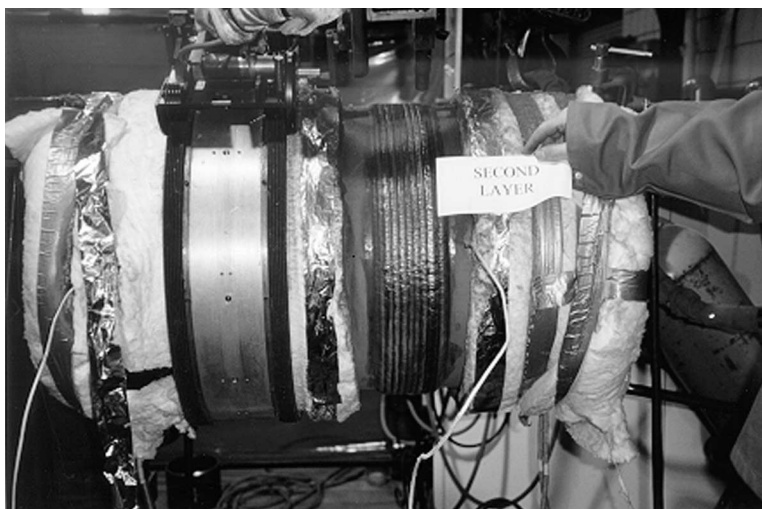


Figure 2-5
Welding After the Second Layer of the One-Half Diameter, Temperbead Weld Development Coupon Completed With Minimal Weave Weld Layers

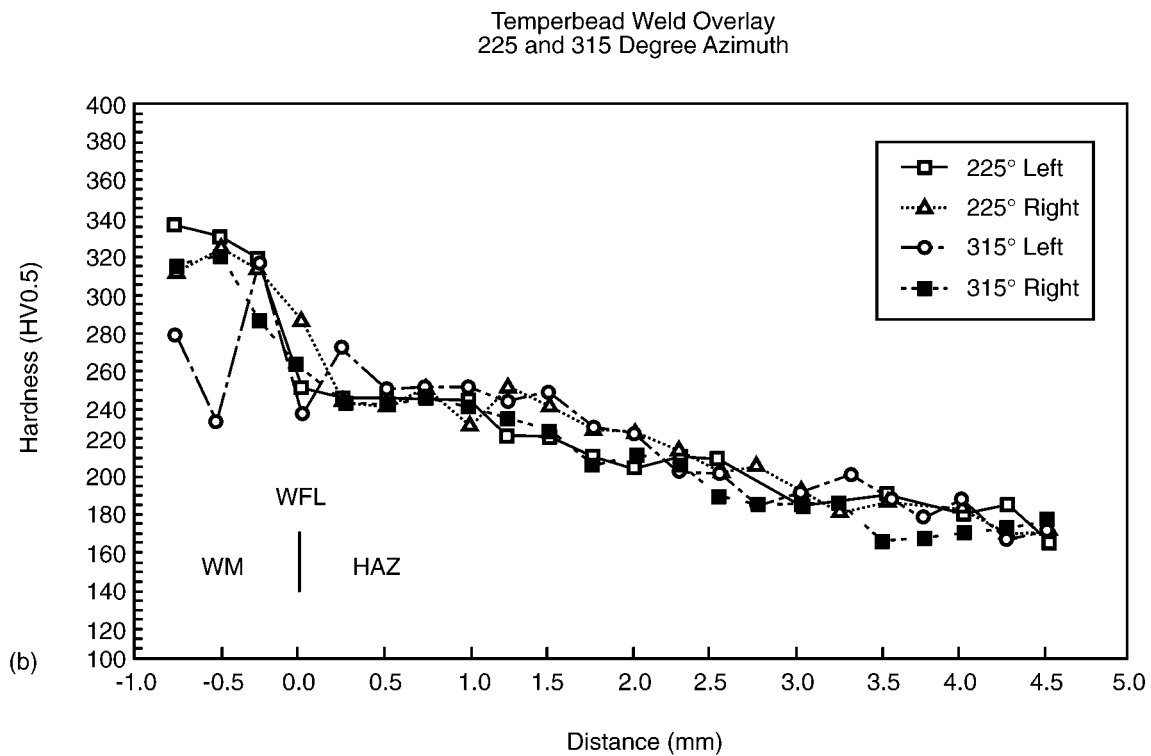
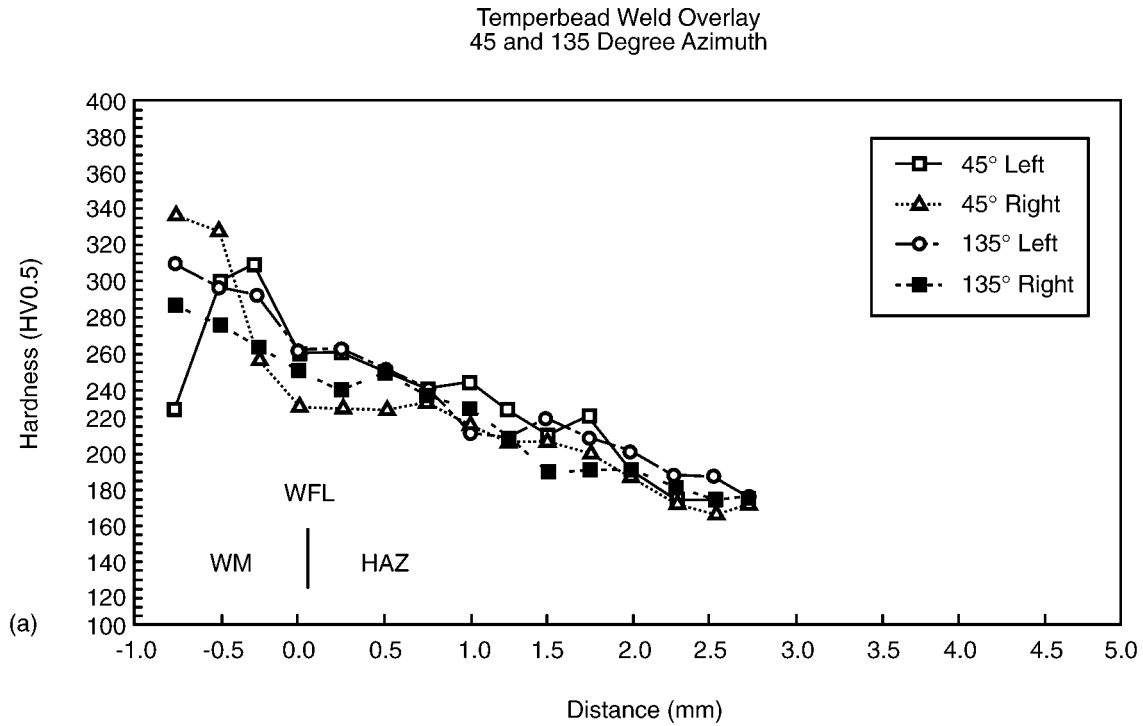
Actual welding parameters for the two mockup sections are provided in Table 2-6. The welds were performed utilizing the Magnatech Pipeliner II welding system, along with the OTC Diahen Fuzzy Auto EXC 350 power supply. A 450F (232C) preheat temperature was employed and no postweld heat treatment was used. Approximately 20 weld beads were required for the stringer overlay, while only 11 were required for the “minimal weave” overlay. Welding progression was in the uphill direction.

Table 2-6
Welding Parameters Employed for Two One-Half Diameter, Temperbead Weld Overlay
Coupons Performed Using a Stringer and a Minimal Weave Approach

	Stringer Overlay	Weave Overlay
Amperage (A)	160	180
Voltage (V)	22.8	24.3
Wire Feed Speed (in/min)	245 (103.7 mm/s)	290 (122.8 mm/s)
Travel Speed (in/min)	15.1 (6.4 mm/s)	6.0 (19.2 mm/s)
Power Ratio (kw/in ²)	141.4 (21.9 kw/cm ²)	56.9 (8.8 kw/cm ²)
Oscillation	N/A	0.25 max
No. of beads/layer	20	11

Upon completion of the welding, mechanical tests were performed for both the HAZ and base metal of each one-half diameter coupon. The tests included hardness, HAZ Charpy impacts, side bends, and metallographic specimens. Hardness traverses were taken beginning at the edge of the weld metal, continuing throughout the HAZ, and finishing just into the base metal. The Vickers hardness (500g) results for each of the four locations 45, 135, 225, and 315 degrees are shown in Figures 2-6a and 2-6b. Maximum recorded values were 258, 258, 241, and 271 Hv, respectively. The average base metal hardness was recorded at 174 Hv.

FCAW Temperbead Welding Development

**Figure 2-6****(a) Vickers Microhardness Test Results for the Stringer Temperbead Weld Overlay****(b) Vickers Microhardness Test Results for the Limited Weave Temperbead Weld Overlay**

Side bend tests were also performed for each of the two one-half diameter overlays. Two coupons were removed from the stringer overlay and two from the weave overlay. All four coupons passed 10X examination following bending.

The next series of tests performed were Charpy impact tests for the base metal and the HAZ of each coupon (Table 2-7). The average base metal impact value for the service-removed, 2-1/4Cr-1Mo steel employed for the weld overlays was 7.5 ft-lbs (10.2 N-m). Average HAZ impact values were recorded at 17.8 ft-lbs (24.1 N-m) (stringer overlay) and 32.0 ft-lbs (43.4 N-m) (limited weave overlay). As can be seen, both easily exceeded the service-removed base metal values.

Table 2-7
Comparison of HAZ Charpy Impact Values for a Stringer and Limited Weave Temperbead Weld Overlay Application on a 2-1/4Cr-1Mo Steel

Sample ID	Charpy Impact Value (ft-lbs)* @ 72F (22C)	Charpy Impact Average (ft-lbs)**
Base Metal	5.5, 6.0, 10.5, 14.0, 3.0, 6.0	7.5
Stringer HAZ	14.0, 13.5, 26.0	17.8
Weave HAZ	33.5, 38.5, 24.0	32.0

*To convert ft-lbs to N-m, multiply the unit by 1.3558.

**No attempt was made to record lateral expansion or percent shear because the FRAC was only comparing the two temperbead approaches.

Due to lower than expected all weld metal Charpy impact properties (less than 13 ft-lbs [18 N-m]), an alternative filler material that would provide values in the 20+ ft-lbs (27+ N-m) range was sought. A FCAW wire, Tri-Mark TM811B2, developed for use in both the as-deposited condition and in the PWHT condition, was obtained. The wire meets the AWS 5.29 specification. An all weld metal pad was fabricated to determine the toughness properties of the weld metal in the as-deposited condition. The results of the testing are shown in Table 2-8.

Table 2-8
Charpy Test Results for an All Weld Metal Coupon Using a Tri-Mark TM811B2 Filler Wire

Sample ID	Charpy Impact Value (ft-lbs)* @ 72F (22C)	Lateral Expansion (mils)	% Shear
A	32	16 (.04 cm)	10
B	25	11 (.03 cm)	0
C	25	12 (.03 cm)	0
	Ave. 27.3 ft-lbs		

* To convert from ft-lbs to N-m, multiply the unit by 1.3558.

As can be seen from the results, the Charpy impact toughness exceeded the 20 ft-lb (27 N-m) restriction that was targeted. In fact, an average value of 27.3 ft-lb (37.0 N-m) was obtained.

Metallographic analyses of the two cross-sectioned specimens from each weldment were performed to verify that no anomalies were present and that good refinement had resulted. Examples of the stringer and minimal weave cross-sections are shown in Figure 2-7.

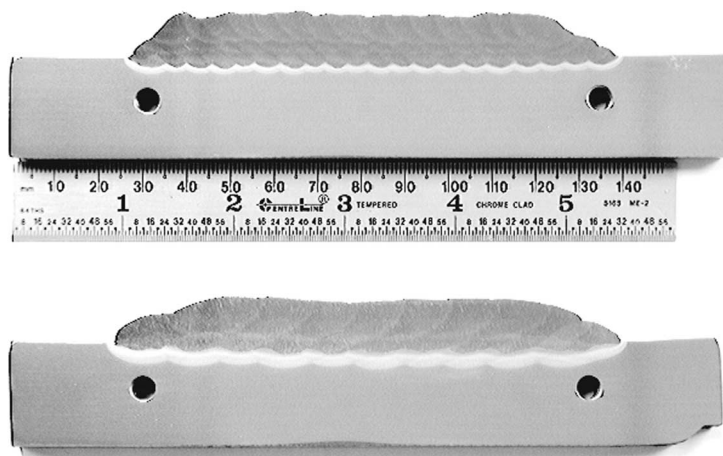


Figure 2-7
Cross-Sections Representing the Stringer and the Minimal Weave Coupons

2.3 Weld Overlay Mockup Demonstration #1

Following the development and demonstration of temperbead welding parameters using the FCAW process, the FRAC initiated work on a full scale, clam shell, elbow mockup. The weld overlay mockup demonstration began with the acquisition of a 38-inch (97-cm) diameter 2-1/8-inch (5.398-cm) thick, 2-1/4Cr-1Mo, hot reheat clam shell elbow from Western Resources Inc. Jeffery Energy Center. The elbow was recently removed from service after 150,000+ hours of operation and 150 starts.

A mockup stand was fabricated to place the elbow at the correct orientation for welding. The stand was fabricated such that the overlay welding could be performed in the overhead-to-vertical welding position as shown in Figure 2-8.

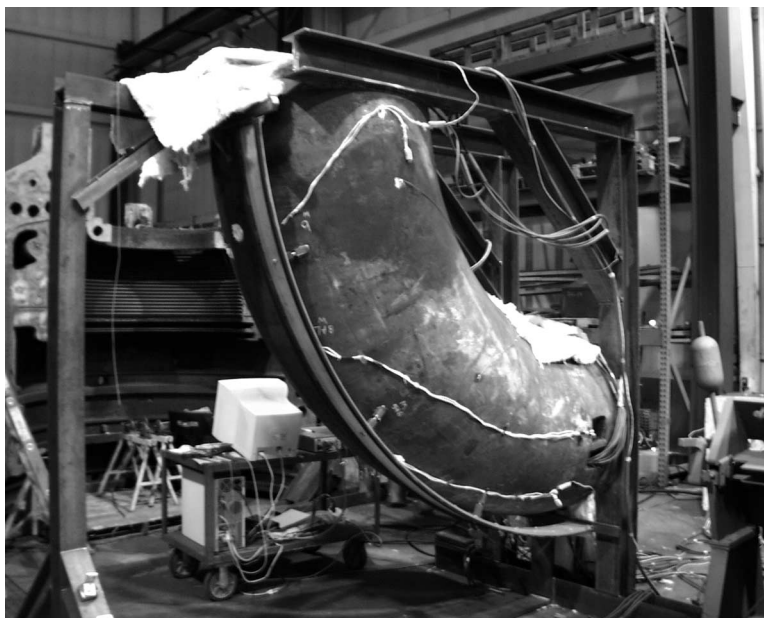


Figure 2-8
Seam Weld Overlay Mockup

Once the mockup assembly was completed, a welding track was acquired from Magnatech and attached to the elbow at various locations along the extrados clam shell weld. Use of the welding track allowed FRAC to utilize the Pipeliner II welding system. An OTC-Diahen Fuzzy Auto EXC 350 power supply was used to power the Pipeliner system.

Following preheating of the elbow to 450F (232C), a three-layer weld overlay was applied along the entire length of the seam weld. The total width of the overlay was 5-3/8-inch (13.653-cm), with an average height of 0.550-inch (1.397-cm) above the surface of the elbow. Approximately 33 lbs (73 kg) of wire were deposited using a 0.045-inch (0.114-cm) diameter AWS A5.29, 81T1-B2 FCAW filler wire (Tri-Mark TM-811B2). Actual arc time was measured at 10.2 hours and a total of 39 weld beads were deposited. The welding began by welding overhead and was completed in the vertical position. No postweld heat treatment was employed. Welding parameters are provided in Table 2-9.

FCAW Temperbead Welding Development

Table 2-9
FCAW Temperbead Welding Parameters for Seam Weld Overlay Mockup

FCAW Temperbead Welding Parameters	
Amperage	180-188 A
Voltage	23.0-23.4 V
Wire Feed Speed (in/min)	285-290 (120-123 mm/s)
Travel Speed (in/min)	6.0 (2.53 mm/s)
Power Ratio (kw/in ²)	56.8 (8.8 kw/cm ²)
Oscillation (inch)	0.250 max (6.35 mm)
Preheat/Interpass Temp.	450F/550F (232C/288C)
Shielding Gas	75Ar/25CO ₂
FCAW Wire Type	Tri-Mark TM-811B2
Wire Diameter (inch)	0.045 (1.14 mm)
Wire Stick-out (inch)	0.75 (19.1 mm)
Total Three Layer Height (inch)	0.550 (14 mm)
No. of Beads/Layer	13
Total Deposit Weight (lbs)	33 (73 kg)

Upon completion of the weld overlay, residual stress measurements were performed and then the overlay was sectioned for mechanical testing. Tensile, bend, and toughness tests were performed and are reported in Tables 2-10 and 2-11.

Table 2-10
Tensile and Bend Test Results for Seam Weld Overlay Mockup

	0.2% Yield Strength (ksi)*	Tensile Strength (ksi)*	% Elongation	% Reduction of Area
Weld Overlay ²	92.4	110.1	19.0	63.0
Weld Overlay ²	97.2	113.9	20.0	60.0
Service-Removed Weld	41.8	66.7	30.0	74.0
Service-Removed Weld	40.3	68.2	33.0	74.0
Side Bends	Two Side Bend Tests—Each Passed			

* To convert ksi to MPa, multiply the unit by 6.895.

Table 2-11
Charpy Impact Toughness Results for Seam Weld Overlay Mockup

	Charpy Impact Strength @ 72F (22C) (Ft-lbs) ³	Lateral Expansion (mils ^{**})	Ductile Fracture Area
Base Metal	15	10.5	0
HAZ	13	20.5	10
Weld Metal	12.3	19.0	10

* To convert from ft-lbs to N-m, multiply the unit by 1.3558.

** To convert from mils to centimeters, multiply the unit by 0.00254.

As can be seen in Table 2-10, acceptable weld tensile and side bend results were achieved for the weld overlay. In the as-deposited condition, very high tensile values (above the 80 ksi (552 MPa) expected range) were actually achieved.

Relatively poor impact toughness properties were measured for base metal, weld metal, and HAZ. The clamshell elbow exhibited only 15 ft-lbs (20 N-m) impact strength, whereas the HAZ and weld metal displayed 13.0 (18 N-m) and 12.3 (16.7 N-m), respectively. Investigators were at first puzzled by the poor performance of the Tri-Mark weld metal because good toughness values were demonstrated on the earlier “weave” development coupon (27.3 ft-lbs [37.0 N-m]). The only explanation that could be hypothesized was that insufficient preheat might have been maintained during the welding.

To test this hypothesis, investigators obtained wire from a second manufacturer, Metrode, which, similar to the Tri-Mark wire, was formulated to be used in either the as-deposited or PWHT condition. The Metrode wire was an E81T1-B2M wire meeting AWS A5.29-98 requirements.

² All weld metal tensile properties

³ Average of four test values

Two weld pad coupons were welded separately using identical parameters to those employed for the TriMark weldments, one with a 450F (232C) preheat and the second a 100F (38C) preheat. Toughness tests were performed upon completion and are reported in Table 2-12.

Table 2-12

Charpy Impact Toughness Results Comparing a Weld Pad Performed With a 450F (232C) Preheat Temperature and a Second Pad Performed at Room Temperature

	Charpy Impact Strength @ 72F (22C) (Ft-lbs)* ⁴	Lateral Expansion (mils)**	% Shear
100F Preheat (38C)	8.2 (ave)	8.5,4.8,5.6	10,0,0
--Longitudinal	15.7 (ave)	6.7,4.0,20.3	5,0,10
--Transverse			
450F Preheat (232C)	32.5 (ave)	-	-
--Longitudinal	56.2 (ave)	-	-
--Transverse			

* To convert from ft-lbs to N-m, multiply the unit by 1.3558.

** To convert from mils to centimeters, multiply the unit by 0.00254.

As shown, a substantial improvement in toughness was realized when comparing the low temperature preheat versus the normal 450F (232C) preheat. Based upon the test results for the Metrode wire, investigators believe the unusually low toughness values recorded for the Tri-Mark wire deposit on the long seam elbow were the result of insufficient preheat temperature maintenance along the entire length of the long seam elbow. Further verification of the hypothesis was to be carried out on a second long seam overlay on a strain section of pipe, which is described in the following section. Also, based upon these results, investigators believe that utilities now have two wires that can be used for FCA weld overlays.

2.4 Weld Overlay Mockup Demonstration #2

In the spring of 2001, an additional welding mockup demonstration was performed to further verify the applicability of the FCAW process to temperbead welding. This demonstration was performed on a piece of straight hot reheat piping removed from a Duke Energy fossil power plant. The pipe was manufactured from SA155 Class D material and had operated 232,621 hours prior to removal. The outside diameter of the pipe was 23 inches (58 cm) and the wall thickness measured about one inch (2.54 cm). Overall length of the pipe spool used for the test was seven feet (2.13 m).

A weld overlay was performed over the existing long seam weldment and consisted of three weld layers with fifteen passes in each layer. Total length of the overlay was 57 inches (145 cm) with an overlay width of 5 inches (12.7 cm). The welding was performed in the 3G position with vertical up progression. The welding preheat temperature employed was 450F (232C) and was performed with resistance heat treatment equipment provided by Thermal Solutions Inc. The

⁴ Average of four test values

equipment was also used to perform a two-hour post bake at 500F (260C) to remove any hydrogen. The welding was performed by Wachs Energy Services Company at their Charlotte facility. A common welding procedure qualification was performed with five visiting utilities during the welding, which is documented under the EPRI longitudinal seam welded piping repair program. An overview of the welding coupon can be seen in Figure 2-9.



Figure 2-9
Seam Weld Pipe Overlay Demonstration Mockup #2

Equipment used in the welding consisted of a welding track from Magnatech and a Pipeliner II welding system. A Panasonic Pana-Star AE 350 power supply was used to power the Pipeliner system. The filler metal used for the welding procedure qualification was supplied by Metrode. The weld required a little over 35 lbs. (77 kg) of wire, which was deposited using a 0.045-inch (0.114-cm) diameter AWS A5.29, 81T1-B2M FCAW filler wire. Actual arc time was about 11 hours. No postweld heat treatment was employed. Welding parameters are provided in Table 2-13.

Table 2-13
FCAW Temperbead Welding Parameters for Seam Weld Overlay Mockup

FCAW Temperbead Welding Parameters	
Amperage (A)	190-200
Voltage (V)	23.0-26.6
Wire Feed Speed (in/min)	285-290 (120-123 mm/s)
Travel Speed (in/min)	6.0 (2.53 mm/s)
Power Ratio (kw/in ²)	63.6 (9.85 kw/cm ²)
Oscillation (inch)	0.250 max (6.35 mm/s)
Preheat/Interpass Temp.	450F/600F (232C/316C)
Shielding Gas	75Ar/25CO ₂
FCAW Wire Type	Metrode 81T1-B2M
Wire Diameter (inch)	0.045 (1.14 mm)
Wire Stick-out (inch)	0.75 (19.1 mm)
Total Three Layer Height (inch)	0.550 (14 mm)
No. of Beads/Layer	13-15
Total Deposit Weight (lbs.)	35 (77 kg)

Upon completion of the weld overlay, residual stress measurements were performed and then the overlay was sectioned for mechanical testing.

Charpy impact toughness results for the weld overlay are reported in Table 2-14. Test results suggest the base metal toughness was 15.3 ft-lbs (20.7 N-m), while an improvement to 19.2 ft-lbs (26.0 N-m) was noted in the weld HAZ. Additionally, transverse and longitudinally oriented Charpy impact coupons were tested resulting in 16.2 and 39.3 ft-lbs (22 and 53.3 N-m). The later test value represents the same orientation as that of the base metal.

Table 2-14
Charpy Impact Toughness Results for Seam Weld Overlay Mockup Demonstration #2

	Charpy Impact Strength @ 72F (22C) (Ft-lbs)⁵	Lateral Expansion (mils)**	Ductile Fracture Area
Base Metal	15.3	14	10
HAZ	19.2	23.3	20
Weld Metal (Transverse)	16.2	16.3	40
Weld Metal (Longitudinal)	39.3	31.7	40

* To convert from ft-lbs to N-m, multiply the unit by 1.3558.

** To convert from mils to centimeters, multiply the unit by 0.00254.

⁵ Average of four test values

3

DISCUSSION

The six temperbead weldments described previously demonstrate that the FCAW process is ideally suited for temperbead welding. With the process, Section IX requirements (bends and tensiles) can easily be met. Additionally, superior toughness and hardness properties can be generated in the weld HAZ and within the weld itself in a similar manner to the SMAW process (which is recognized by NBIC under RD-1000 Welding Methods 2 & 4).

Wire fed processes including GTAW-AU, GMAW, and FCAW are uniquely suited for temperbead welding applications in that consistent weld layers can be deposited with little difficulty. As a result, consistent tempering profiles are generated between weld layers. With the FCAW process, welding heat and weld puddle size are always directly related to the input power and deposited area (more on this topic below). These, in turn, are directly related to the tempering experienced during application of successive weld layers. FCA welding, if applied with the proper weld overlap (50%), will produce excellent HAZ and weld properties.

In wire-fed processes, tempering of the weld HAZ and of each individual layer can be accurately controlled via adjustment of welding *input power* (amperage x voltage) versus the *deposited area* (wire feed speed/travel speed x cross-sectional area of wire) [10]. This relationship of input power to deposited area is defined as *power ratio*. Within a given range of the power ratio, acceptable toughness, hardness, and tensile properties can be consistently achieved for any given carbon or low alloy steel.

The power ratio approach has been studied extensively for the GTAW process and is reported in EPRI report TR-103354 [10]. With this approach, users are able to accurately define the following welding characteristics:

- Cross-sectional area of deposited metal
- Weld dilution
- Total weld bead cross-sectional area (weld nugget area)
- Power input level for a given area of deposited metal

Use of the power ratio approach for the FCAW process will provide similar control of welding characteristics as for the GTAW process. The primary difference is that with the FCAW process, amperage and travel speed are often dependent parameters. A change in amperage is accompanied by a similar change in travel speed, whereas, with the GTAW process, the two parameters are independent of one another. Regardless, the power ratio calculation can be applied to control the welding energy versus the deposited metal and dilution.

Discussion

A number of temperbead weld procedures have been developed and are discussed herein. The procedures have employed both stringer and minimal weave (oscillation) methods to provide good properties. Stringer applications have been shown to use welding power ratio values of almost 2-3X that of minimal weave applications. The latter has been shown to provide greater control for performing “out-of-position” welds (such as might be encountered in automated or semi-automated pipe welding) and is more welder-friendly. Minimal weave provides for improved arc stability and mitigates the inadequate tempering problems often associated with wider weave applications. The specific power ratio range for the minimal weave applications investigated herein is fairly broad ranging from 48 to 64 kw/in² (310 to 413 kw/cm²).

This power ratio range represents a very practical range of parameters from 160 to 200 amperes. It is believed this range can be expanded with additional testing to as low as 100 amperes and to greater than 250 amperes. The important factor is to maintain a consistent ratio of power to deposited area (that is, power ratio) sufficient to provide acceptable tempering of carbon and low alloy steels.

Stringer applications have also been shown to produce acceptable HAZ and weld tempering. More recent EPRI applications have tended to shy away from use of stringer FCA welding because minimal weave applications provide the welder with improved control of the welding puddle and arc stability. If welding is performed in a single welding position (that is, vertical), stringer bead applications are, however, considered acceptable.

Limits on Hydrogen

Significant improvements have occurred over the past five years in the FCAW process. These improvements are related primarily to two changes:

- The introduction of better controls on hydrogen in filler materials
- Improved power supplies with inverter capabilities

The introduction of improved manufacturing methods and controls has significantly altered FCAW filler wires. Wires are more consistent in chemistry and as a result demonstrate more uniform diffusible hydrogen levels.

Users are now able to order from the wire manufacturer a designated diffusible hydrogen level of a FCAW wire for a specific application [11]. A diffusible hydrogen designator such as H16, H8, or H4 (indicating maximum limits of 16, 8, and 4 ml of hydrogen per 100 grams of deposited metal) can be stipulated by the user. For low alloy steels, the user should specify ASME Section II, Part C, SFA 5.29, “Specification for Low Alloy Electrodes for Flux-Cored Arc Welding.”

One factor that users should consider is the storage of FCAW consumables. FCAW wires over time will absorb moisture, which can manifest itself as diffusible hydrogen during welding. It is recommended that only new wires with controlled hydrogen levels be considered for power boiler (P-No. 4 and P-No. 5A) temperbead welding. In lieu of purchasing new hydrogen controlled wires, users are advised to control FCAW wires in ovens similar to SMAW rod ovens.

4

FLUX-CORED ARC WELDING PROCEDURE SPECIFICATION

The following provides information pertaining to a recommended Welding Procedure Specification for using the FCAW process [12]:

1. The welding preheat temperature requirements found in *RD-1060 Welding Method 4, Item h.1* for SMAW is also appropriate for FCAW.
2. Welding Technique
 - Consistent welding parameters (amperage, voltage, wirefeed speed, and travel speed, within plus/minus 5%) should be employed for all weld layers.
 - Oscillation or weave should be limited to 0.25-inch (0.64-cm) maximum to improve arc stability and provide improved out-of-position control. Minimal weave is recommended over stringer beads.
 - For temperbead applications, a power ratio of 48 to 64 kw/in² (310 to 413 kw/cm²) represents an acceptable range for welding with minimal weave (0.25-inch [6.4 mm] max).
 - No fewer than three layers should be allowed for any weld buildup. Two layers are adequate to provide acceptable HAZ properties.
3. Welding Consumables
 - 0.045-inch (1.14 mm) diameter outer-shield FCAW wire or greater is considered acceptable. Hydrogen limits of H16, H8, or H4 are required.
 - Users are advised to control FCAW wires in ovens to eliminate potential absorption of moisture. When wires are not in use (for example, overnight) they should be placed back into an oven. Metallic spools are necessary to maintain wire in ovens.
 - 75Ar/25CO₂ shielding gas is recommended (P-No. 4 and P-No. 5A only). Other shielding gases might also be acceptable.
4. Hydrogen bake-out recommendations found in *RD-1060 Welding Method 4, Item h.3* for the SMAW is appropriate for FCAW.
5. Item h.4 pertaining to grinding of the final layer should be omitted.

5

SUMMARY

Presently, NBIC Welding Method 2, which is used when the applicable rules of the original code of construction require notch toughness testing, permits the use of several welding processes including SMAW, GMAW, GTAW, and FCAW. Welding Method 4, which is used for power boiler applications (with P-No. 4, Groups 1 and 2, and P-No. 5A) as permitted for welded construction by the applicable rules of original construction, is limited strictly to the SMAW welding process. Both methods recognize temperbead welding to generate weld and HAZ properties in lieu of PWHT.

This paper has presented at least six cases where FCAW has been shown to provide acceptable (and often superior) mechanical properties to that of the base metal. Comprehensive test data, along with welding parameters, have been provided for each case.

Based upon this data and the precedent established under Welding Method 2, where multiple welding methods are permitted, it is recommended that NBIC should consider amending Welding Method 4 to permit the use of the FCAW process. Furthermore, although no data has been presented to support this position in this paper, it is recommended that GTAW should also be incorporated. Considerable data has been generated by the industry supporting the use of GTAW for temperbead welding. The process has been shown to be more forgiving because the wire does not provide a source for hydrogen in the weld puddle; thus, hydrogen is limited to the H4 range or lower [10].

6

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12. *Assessment of Storage Requirements for Electrodes and Spooled Wires*. EPRI, Palo Alto, CA: October 1999, pp. 3-10 through 4-2. TE-112931.

A

**NATIONAL BOARD INSPECTION CODE RD-1000
WELDING METHODS AS ALTERNATIVES TO
POSTWELD HEAT TREATMENT**

PART RD - REPAIR METHODS

**PART RD
REPAIR METHODS****RD-1000 WELDING METHODS AS ALTERNATIVES TO
POSTWELD HEAT TREATMENT****RD-1010 SCOPE**

- a. Under certain conditions, postweld heat treatment in accordance with the original code of construction may be inadvisable or impractical. In such instances, the following alternative methods may be used.
- b. Competent technical advice shall be obtained from the manufacturer of the pressure retaining item or from another qualified source, such advice being especially necessary if the alternative is to be used in highly stressed areas, if service conditions are conducive to stress corrosion cracking, if materials are subject to hydrogen embrittlement or are operating at temperatures in the creep range, or if the alternative is being considered for "on-stream" repairs or "hot tapping" on piping systems. Selection of the welding method used shall be based on the rules of the original code of construction together with the above mentioned advice concerning the adequacy of the weld in the as-welded condition at operating and pressure test conditions.
- c. When reference is made in this part to materials by the ASME designation, P-Number and Group Number, the requirements of this part apply to the applicable materials of the original code of construction, either ASME or other, which conform by chemical composition and mechanical properties to the ASME P-Number and Group Number designations.

**RD-1020 NONDESTRUCTIVE
EXAMINATION OF WELDS**

Prior to welding, the area prepared for welding shall be examined using either the

magnetic particle (MT) or the liquid penetrant (PT) examination method to determine that no defects exist. After the finished repair weld has reached ambient temperature, the weld shall be examined again by either of the above methods to determine that no defects exist using acceptance standards acceptable to the Inspector or original code of construction. In addition, welded repairs greater than 3/8 in. (9.6 mm) deep or welds in a boiler, pressure vessel or piping systems that were originally required to be radiographed by the rules of the original code of construction, shall be radiographically examined. In situations where it is not practical to perform radiography the accessible surfaces of each nonradiographed repair weld shall be fully examined using the MT or PT method to determine that no defects exist, and the maximum allowable working pressure and/or allowable temperature shall be reevaluated to the satisfaction of the jurisdiction at the location of installation.

RD-1030 WELDING METHOD 1

- a. This method may be used when the applicable rules of the original code of construction did not require notch toughness testing.
- b. The materials shall be limited to P-No. 1, Group 1, 2, and 3, and to P-No. 3, Group 1 and 2 (excluding Mn-Mo steels in Group 2), as permitted for welded construction by the applicable rules of the original code of construction.
- c. The welding shall be limited to the shielded metal-arc welding (SMAW), gas metal-arc welding (GMAW), fluxcored arc welding (FCAW) and gas tungsten-arc welding (GTAW) processes.

NATIONAL BOARD INSPECTION CODE

- d. The welders and welding procedures (WPS) shall be qualified in accordance with the applicable rules of the original code of construction, except that the post-weld heat treatment of the test coupon used to qualify the weld procedure shall be omitted.
- e. The weld area shall be preheated and maintained at a minimum temperature of 300°F (149°C) during welding. The 300°F (149°C) temperature should be checked to assure that 4 in. (102 mm) of the material or four times the material thickness (whichever is greater) on each side of the groove (or full thickness of joint for a groove weld) is maintained at the minimum temperature during welding. The maximum interpass temperature shall not exceed 450°F (232°C). When the weld does not penetrate through the full thickness of the material, the minimum preheat and maximum interpass temperatures need only be maintained at a distance of 4 in. (102 mm) or four times the depth of the repair weld, whichever is greater on each side of the joint.
- c. The welding shall be limited to the shielded metal-arc welding (SMAW), gas metal-arc welding (GMAW), fluxcored arc welding (FCAW) and gas tungsten-arc welding (GTAW) processes.
- d. The welders and welding procedures (WPS) shall be qualified in accordance with the applicable rules of the original code of construction, except that the post-weld heat treatment of the test coupon used to qualify the weld procedure shall be omitted. The qualification thickness for the test plates and repair grooves shall be in accordance with Table I.
- e. As shown in Table I, the depth of the repair groove (or full thickness of a joint for a groove weld) in base metal or in weld metal is not limited provided the test material thickness for the welding procedure qualification is at least five times the depth of the repair but need not exceed the thickness of the material to be repaired, provided the required test specimens can be removed. When the thickness of the base metal to be repaired is greater than 2 in. (51 mm), the procedure qualification test material need not exceed 2 in. (51 mm); however, the depth of the groove in the test material shall be the greater of 1 in. (25 mm) or the depth of the groove to be repaired.

RD-1040 WELDING METHOD 2

- A 99 a. This method shall be used when the applicable rules of the original code of construction required notch toughness testing or shall be used when the applicable rules of the original code of construction did not require notch toughness testing provided the adequacy of the notch toughness of the weld, including the heat-affected zone, in the as welded condition at operating and pressure test conditions is verified.
- A 99 b. The materials shall be limited to carbon and low alloy steels permitted for welded construction by the applicable rules of the original code of construction, including those materials conforming to any of the following ASME P-No. designations: P-No. 1, Group 1, 2 and 3, P-No. 3, Group 1, 2 and 3, P-No. 4, P-No. 5A, P-No. 5B, P-No. 5C, P-No. 9A, P-No. 10A, P-No. 11A, or P-No. 11B.
- f. The test material for the welding procedure qualification shall be of the same material specification (including specification type, grade, class and condition of heat treatment) as the original material specification for the repair. In the event that the notch toughness of the material to be repaired is unknown, evidence from tests of that material or from another acceptable source (see RD-1010) may be used for the base metal notch toughness when qualifying the WPS as required in (g). In the event that the original material specification is obsolete, the test material used should conform as close as possible to the original material used for construction.

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National Board Inspection Code RD-1000 Welding Methods as Alternatives to Postweld Heat Treatment

PART RD - REPAIR METHODS

tion, but in no case shall the material be lower in strength.

- g. The organization making the repair shall include, when qualifying its WPS, sufficient tests to determine that the toughness of the weld metal and the heat-affected zone of the base metal in the as-welded condition is adequate at the minimum operating and pressure test temperatures (including start-up and shut-down). When these conditions are met, any original code of construction credit for PWHT may be continued. If for reasons of corrosion resistance, special hardness limits are necessary, such limits shall be included when qualifying the WPS.
- h. Notch toughness shall be determined and evaluated by Charpy impact tests in accordance with the provisions of the original code of construction.
- i. The WPS shall include the following additional requirements:
 - 1. The supplemental essential variable of ASME Code, Section IX, paragraph QW-250, shall apply;
 - 2. The maximum weld heat input for each layer shall not exceed that used in the procedure qualification test;
 - 3. The minimum preheat temperature for welding shall not be less than that used in the procedure qualification test;
 - 4. The maximum interpass temperature for welding shall not be greater than that used in the procedure qualification test;
 - 5. The preheat temperature shall be checked to assure that 4 in. (102 mm) of the material or four times the material thickness (whichever is greater) on each side of the weld joint will be maintained at the minimum temperature during welding. When the weld

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does not penetrate through the full thickness of the material, the minimum preheat temperature need only be maintained at a distance of 4 in. (102 mm) or four times the depth of the repair weld, whichever is greater on each side of the joint;

- 6. For the welding process in (c) above, use only electrodes and filler metals which are classified by the filler metal specification with an optional supplemental diffusible-hydrogen designator of H8 or lower. When shielding gases are used with a process, the gas shall exhibit a dew point that is no lower than -60 F (-50 C). Surfaces on which welding will be done shall be maintained in a dry condition during welding and be free of rust, mill scale and hydrogen producing contaminants such as oil, grease and other organic materials.
- 7. The welding technique shall be a controlled-deposition, temper bead or half bead technique. The specific technique or specific combinations of techniques shall be that used in the procedure qualification test;
- 8. For welds made by SMAW and FCAW, after completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment shall be raised a temperature of 500 F $\pm$ 50 F (260 C $\pm$ 30 C) for a minimum period of two hours. This hydrogen bake-out treatment may be omitted provided the electrode used is classified by the filler metal specification with an optional supplemental diffusible-hydrogen designator of H4 (e.g., E7018-H4); and
- 9. After the finished repair weld has cooled to ambient temperature, the final temper bead reinforcement layer shall be removed substantially flush with the surface of the base material.

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RD-1050 WELDING METHOD 3

- a. This method may be used when the applicable rules of the original code of construction did not require notch toughness testing.
- b. The materials shall be limited to any P-No. 1 or P-No. 3 material as permitted for welded construction by the applicable rules of the original code of construction.
- c. The welding shall be limited to the shielded metal-arc welding (SMAW) and gas tungsten-arc welding (GTAW) processes.
- d. The welders and welding procedures (WPS) shall be qualified in accordance with the applicable rules of the original code of construction, except that the post-weld heat treatment of the test coupon used to qualify the weld procedure shall be omitted. The qualification thicknesses for the test plates and repair grooves shall be in accordance with Table I.
- e. As shown in Table I, the depth of the repair groove (or full thickness of a joint for a groove weld) in base metal or in weld metal is not limited provided the test material thickness for the welding procedure qualification is at least five times the depth of the repair but need not exceed the thickness of the material to be repaired, provided the required test specimens can be removed. When the thickness of the base metal to be repaired is greater than 2 in. (51 mm), the procedure qualification test material need not exceed 2 in. (51 mm); however, the depth of the groove in the test material shall be the greater of 1 in. (25 mm) or the depth of the groove to be repaired.
- f. The test material for the welding procedure qualification shall be of the same P-No. and Group No. as the original material specification for the repair. In the event that the original material specification is obsolete, the test material used should conform to the nominal composition and carbon equivalent (IIW formula) as the original material used for construction, but in no case shall the material be lower in strength.
- g. If for reasons of corrosion resistance, special hardness limits are necessary, such limits shall be included when qualifying the WPS.
- h. The WPS shall include the following additional requirements:
 1. The maximum weld heat input for each layer shall not exceed that used in the procedure qualification test;
 2. The minimum preheat temperature for welding shall be 350F (177C) and the maximum interpass temperature shall be 450F (232C);
 3. For SMAW, only electrodes with low hydrogen characteristics shall be used;
 4. The welding technique shall be a controlled-deposition, temper bead or half bead technique. The specific technique or specific combinations of techniques shall be that used in the procedure qualification test;
 5. For SMAW the electrode size shall not exceed 1/8 in. (3.2 mm) and for GTAW the electrode size and the filler metal size shall not exceed 3/32 in. (2.4 mm);
 6. For welds made by SMAW, after completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment shall be raised to a temperature of 500 F $\pm$ 50 F (260 C $\pm$ 30 C) for a minimum period of two hours. This hydrogen bake-out treatment may be omitted provided the electrodes used are classified by the filler metal specification

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with an optional supplemental diffusible-hydrogen designator of H4 (e.g., E7018-H4); and

7. After the finished repair weld has cooled to ambient temperature, the final temper bead reinforcement layer shall be removed substantially flush with the surface of the base material.

A 99 RD-1060 WELDING METHOD 4

- A 00** a. This method is limited to boilers for which the applicable rules of the original code of construction did not require notch toughness testing.

- b. The materials shall be limited to P-No. 4, Groups 1 and 2 and P-No. 5A steels as permitted for welded construction by the applicable rules of the original code of construction.

- c. The welding shall be limited to the shielded metal-arc welding (SMAW) process using low hydrogen electrodes classified by the filler metal specification with an optional supplemental diffusible-hydrogen designator of H8 or lower and suitably controlled by maintenance procedures to avoid contamination by hydrogen producing sources. The surface of the metal prepared for welding shall be free of contaminants.

- d. The welders and welding procedures shall be qualified in accordance with the applicable rules of the original code of construction, except that the postweld heat treatment of the test coupon used to qualify the weld procedure shall be omitted.

- e. As shown in Table I, the depth of the repair groove (or full thickness of a joint for a groove weld) in the base metal or in weld metal is not limited provided the test material thickness for the welding procedure qualification is at least five times the depth of the repair but need not exceed the thickness of the material to be repaired, provided the required test specimens can be

removed. When the thickness of the base metal to be repaired is greater than 2 in. (51 mm), the procedure qualification test material need not exceed 2 in. (51 mm); however, the depth of the groove in the test material shall be the greater of 1 in. (25 mm) or the depth of the groove to be repaired.

- f. The test material for the welding procedure qualification shall be of the same P-No. and Group No. as the original material specification for the repair. In the event that the original material specification is obsolete, the test material used shall conform to the nominal composition and carbon equivalent (IIW formula) as the original material used for construction, and in no case shall the material be lower in strength.

- g. If for reasons of corrosion resistance, special hardness limits are necessary, such limits shall be included when qualifying the WPS.

- h. The WPS shall include the following additional requirements:

1. The minimum preheat temperature for welding shall be 300 F (150 C) for P-No. 4 material and 400 F (200 C) for P-No. 5A material. The preheat temperature shall be checked to assure that 4 in. (100 mm) of the material or four times the material thickness (whichever is greater) on each side of the groove (or full thickness of joint for a groove weld) is maintained at the minimum temperature during welding. The maximum interpass temperature shall not exceed 800 F (430 C). When the weld does not penetrate through the full thickness of the material, the minimum preheat and maximum interpass temperature need only be maintained for 4 in. (100 mm) or four times the depth of the repair weld (whichever is greater) on each side of the joint.

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2. The welding technique shall be a controlled-deposition temper bead technique and shall include a buttering layer deposited over the entire groove faces (or fillet leg faces) using a 3/32 in. (2.4 mm) diameter electrode. The buttering layer shall be deposited using stringer beads with an overlap of approximately 50%. The second and remaining layers shall be deposited over the buttering layer using a 1/8 in. (3.2 mm) diameter electrode. The second and remaining layers shall not contact the base material and shall be deposited using stringer beads. After the groove is filled (or fillet size is achieved), a 1/8 in. (3.2 mm) thick reinforcement layer shall be deposited to temper the prior weld layer. This temper layer shall be deposited to within 1/8 in. (3.2 mm) of the toe of the weld, but no closer than 1/16 in. (1.6 mm).
3. After completion of welding and without allowing the weldment to cool below the minimum preheat temperature, the temperature of the weldment shall be raised to a temperature of 500 F $\pm$ 50 F (260 C $\pm$ 30 C) for a minimum period of two hours. This hydrogen bake-out treatment may be omitted provided the electrode used is classified by the filler metal specification with an optional supplemental diffusible-hydrogen designator of H4 (e.g., E7018-H4).
4. After the finished repair weld has cooled to ambient temperature, the final temper bead reinforcement layer shall be removed substantially flush with the surface of the base metal (and for a fillet weld to the required size and suitable contour of the toes).

PART RD - REPAIR METHODS

TABLE I
WELDING METHODS AS ALTERNATIVES TO POSTWELD
HEAT TREATMENT
QUALIFICATION THICKNESSES FOR TEST PLATES AND REPAIR GROOVES

BASE METAL THICKNESS	REPAIR GROOVE DEPTH	PQR TEST MATERIAL THICKNESS	PQR GROOVE DEPTH NOTE (2)	THICKNESS QUALIFIED NOTE (1)
<2"	<1"	5 times the repair cavity depth, but need not exceed the thickness of the base metal to be repaired	<1"	See PQR test material thickness column and $\leq$ PQR groove depth
$\leq 2"$	>1"	Thickness of the base metal to be repaired	>1"	$\leq$ PQR test material thickness and $\leq$ PQR groove depth
>2"	1"	2"	1"	All base metal thickness and $\leq 1"$ repair groove depth
>2"	>1"	2"	>1"	All base metal thickness and $\leq$ PQR groove depth

1. Repair groove depth is limited to the maximum depth qualified.
2. The depth of the groove used for procedure qualification must be deep enough to remove test specimens.

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