Evaluations of Half-Bead Weld Repair Procedures
With Thick-Wall Pressure Vessels*

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Abstract

The results of research on the evaluation of the half-bead weld repair method for use on nuclear reactor components are reviewed from data obtained on thick-section test pieces and intermediate-size pressure vessels. Material properties, the magnitude of residual stresses and the structural behavior of flawed pressure vessels are being obtained to determine the adequacy of the weld repair method for application in thick-section components.

1. Introduction

The need for an inservice surveillance of nuclear components was recognized by the ASME Boiler and Pressure Vessel Code (Code). This need resulted in the preparation of Section XI of the Code, "Rules for Inservice Inspection of Nuclear Power Plant Components" [1]. The probability that crack-like indications would be detected by the required nondestructive examinations prompted the Code Committee to prepare Article IWB-4000 Repair Procedures for inclusion in Section XI. The repair procedures permit the in-situ removal and repair of crack-like indications without the requirements for the post-weld heat treatment (PWHT) that are mandatory in Subsection NB of Section III of the Code. Table NB-4622.1-1 dictates the temperature range and minimum holding times for the fabrication of Class 1 pressure vessels and piping.

Repairs made in accordance with the requirements of Article IWB-4000 of Section XI eliminates the need for a post-weld heat treatment. The procedure is entitled "the half-bead weld repair" but is more definitively described by the name "temper bead repair." Figure 1 schematically describes the procedure permitted in IWB-4423 of Section XI. Initially, the crack is removed, the cavity ground smooth and inspected (Fig. 1a). The cavity is then buttered using a 2.4-mm-diam shielded metal arc (SMA) electrode (Fig. 1b). Approximately one-half the thickness of this buttered layer is removed by grinding (Fig. 1c). The ground layer is inspected by magnetic particle (MT) examination and a second layer is deposited with a 3.2-mm-diam electrode. The second weld pass with the 3.2-mm-diam electrode tempers the heat-affected zone (HAZ) in the base metal that occurred as a consequence of the butter layer. The cavity is then filled with subsequent SMA weld passes using either a 3.2- or 4.0-mm electrode. It is mandatory in the Code that each subsequent layer be examined by MT.

The Code requires that the welding procedure and welders be qualified in accordance with Section IX of the Code <u>and</u> the additional requirements of Article IWB-4423 of Section XI. The qualification repair weld provides sufficient material to conduct the required side-bend, Charpy V-notch and tensile tests necessary for acceptance.

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The Heavy-Section Steel Technology (HSST) program administered by the Oak Ridge National Laboratory has pressure tested eight intermediate vessels [2]. The intermediate test vessels (ITV) were fabricated from either SA508 class 2 or SA533, grade B, class 1 steel. The ITVs contain a test course that is 1.4-m long, 700-mm inside diameter, and a wall thickness of 152 mm. The primary objective of these tests is to verify methods of fracture prediction where carefully defined and sharpened flaws are present and complete material characterizations have been performed. Extensive measurements of strain and crack-opening displacement are obtained during the tests supplemented by information on crack extension determined by ultrasonic and acoustic emission techniques. ITV-7 contained a flaw that was 472-mm long at the outside surface (330-mm average length) and 135-mm deep [3,4]. This vessel was initially hydraulically tested at 91°C (the ductile upper shelf temperature) until leakage occurred. The vessel had undergone very little strain and it was decided that it should be salvaged and tested pneumatically under identical conditions. In order to reuse the vessel, it was necessary to repair the leak without imposing an elevated temperature PWHT. It was decided that the half-bead weld repair procedure of Section XI would permit the HSST program to salvage the vessel. A half-bead weld repair was made and the vessel was retested pneumatically. This test, ITV-7A, was pressurized at 88°C until leakage occurred. The vessel was once again salvaged by repairing the leak from the second test using the half-bead procedure. The vessel was tested a third time with the same size flaw (472-mm long, 135-mm deep) oriented so that the crack tip at the terminus of the flaw resided in the HAZ of the repair weld.

In addition to the through-the-wall repairs made on ITV-7A and ITV-7B, a second vessel, ITV-8, was given a simulated repair. The repair in ITV-8 was located so that the repair weld resided in both the base metal and the original vessel fabrication weld. The location of the ITV-8 repair in reference to the fabrication weld is shown in Fig. 2.

The repair weldments were performed in accordance with the procedures prescribed by Subarticle IWB-4420 of Section XI of the Code. An ORNL welding specification based on this procedure was prepared for the repairs and details of the work can be found in Ref. [5]. This procedure was developed with the advice of the PVRC Advisory Task Group on Weld Repair of Pressure Vessels. The first repair on vessel V-7 was performed by Combustion Engineering, Inc., through a subcontract with the Electric Power Research Institute. The second repair of this vessel and the repair of vessel V-8 was performed by Westinghouse Tampa Division. A principal difference between the two welding operations was the position of the work. The first vessel repair was performed with the flaw axis in the flat position (1G) and the last two repairs were performed with the flaw axes in the vertical position (3G).

2. Materials Characterization

The qualification welds (weld metal test plates and the vessel prolongations) were used to characterize the mechanical properties of the weld repairs. Tensile strength, Charpy V-notch (C_V), hardness and fracture toughness tests were made to provide a complete characterization of the half-bead repair weld metal and base metal HAZ.

The room temperature, yield and ultimate tensile strengths of the weld metal were 496 and 588 MPa, respectively. At the 87°C test temperature of ITV-7B these values were 485 and 575 MPa, respectively. The weld metal specimen axes were oriented perpendicular to the direction of welding (transverse orientation).

The fracture energy of the weld metal using C_V specimens was 68 joules at −46°C and 180 joules on the upper shelf. Onset of the C_V upper shelf energy occurred at approximately 38°C. The fracture toughness of the weld metal was also determined through the use of precracked Charpy-V specimens (PCC_V). The weld metal exhibited 100 $MN \cdot m^{-3/2}$ at −90°C. The maximum fracture toughness (∿250 $MN \cdot m^{-3/2}$) was observed near 0°C.

An extensive PCC_V investigation was conducted to determine the fracture toughness of the part-through repair in ITV-8. This study required that the fatigue cracks in the PCC_V specimens be precisely oriented in respect to the base metal-repair weld HAZ and the repair weld-fabrication weld HAZ. These interfaces are identified as A-A and B-B in Fig. 2. The original fabrication weld-base metal HAZ was also investigated (location C-C in Fig. 2). In addition to the PCC_V tests, hardness traverses were made at these same three interfaces.

The fracture toughness of these locations were compared at −46°C. Table 1 provides the fracture toughness values obtained at each of these locations. Table 1 also summarizes the results of the hardness traverse across these interfaces.

3. Residual Stress Determinations

Residual stress measurements were made on each of the vessels and the respective simulation welds in the cylindrical prolongations [6]. The findings from this work revealed relatively high residual stresses in the base metal and fabrication weld adjacent to the repair weld while the stresses in the repair weld metal proper were low. Strain gages were attached adjacent to the weld cavity to measure strain changes that occurred because of the welding. The peak stresses calculated from these strains were near yield. The peak circumferential tensile stresses of about 450 MPa were determined to exist approximately 40 mm from the fusion line of the repair weld. Through-the-thickness measurements were made on the prolongations after cutting the sections in half. The hole-drilling technique was used to obtain the residual stress pattern throughout the section. Appropriate corrections for sectioning were made.

The results from one of these evaluations of residual stress in a repair weld volume is shown in Fig. 3. This figure illustrates the relatively low stresses in the repair volume and the peaking of stress external to the repair. These results were contrary to original expectations since the residual stresses were relatively low in the weld metal and, in fact, were insignificant for the part-through weld repair volume as shown.

The hole drilling technique required considerable development and characterization, particularly with regard to surface preparation and the mechanics of introducing the drilled hole. The results of this technique agreed favorably with the measurements made with surface strain gages and the technique was qualified with stress free sections and members containing known stresses.

The vessel test, ITV-7B, which contained the flaw in the HAZ, was tested at 87°C; a temperature nearly identical to the previous two tests with a similar flaw configuration. A stainless steel patch was welded on the inside surface underneath the flaw to prevent leakage after ligament tear-through so that the load could be sustained. The vessel behaved as expected during pressurization with good agreement between predictions of crack-opening displacement and first leakage through the ligament. The test conditions and results for the three similar vessel tests are summarized in Table 2. Two types of failures were estimated: leakage without burst and instability of the flaw by axial propagation followed by a burst. The predicted ligament rupture pressure was 143 MPa. Taking account of the effects of bulging and using the Irwin β_c correction for the lack of transverse restraint, it was calculated that the pressure would have to exceed the through-thickness yielding pressure in an unflawed cylinder, 190 MPa, for a burst to occur with a flaw 330 mm in length.

In the case of ITV-7B, tensile properties of the repair weld metal as shown in Table 3 and the fracture toughness of HAZ were compared with the plate material in which the flaws were located in the previous two vessel tests. The yield stress in the weld metal fell within the plate values which ranged from 434 MPa in the center to 517 MPa near the surface. Fracture toughness of the plate material was generally lower, 192 to 268 $MN \cdot m^{-3/2}$, than the HAZ, 254 to 382 $MN \cdot m^{-3/2}$.

Residual tensile circumferential stresses which peaked at approximately 200 MPa in the region of the flaw, were not predicted to influence ligament rupture significantly since it had already been determined that ligament strains exceeded yield strain prior to failure of the ligament. With the slightly higher toughness of the HAZ initial tearing was probably retarded since ITV-7B leaked at the highest pressure. A burst was not predicted and did not occur; however, the resistance to tearing, once tearing was established, was apparently less than the previous vessel tests. Post-test examination of the flaw revealed that the crack did follow the weld-base metal interface and the extensions were of the order of 100 mm.

4. Conclusions

The work performed indicates that the material properties of the weld repairs performed by the half-bead technique are quite satisfactory. The assessment of the repair weldments was conducted through the use of fracture tests and metallographic examinations. It was determined that the HAZ in the base metal of the repair weld was equivalent or superior in fracture toughness to any other region. It was determined that residual stresses approaching the yield strength are present; however, the maximum stress occurred approximately 40 mm outside the repair weld. Pressure testing of weld-repaired vessels did not reveal any deficiency, and the vessels sustained overload pressures as predicted.

Additional analyses and another vessel test (ITV-8) are planned. In order to obtain more information on the effect of residual stress on flawed vessel behavior, the ITV-8 test will be conducted in the transition temperature regime where the superimposed loads of the residual stresses will influence flaw behavior more significantly.

References

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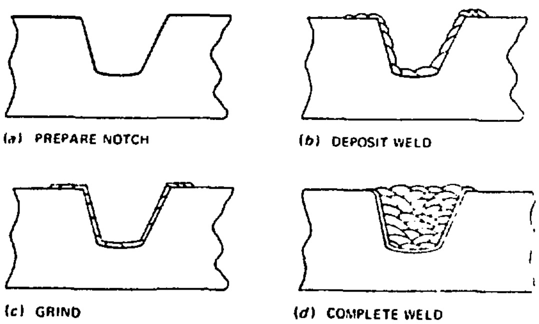

Fig. 1. A schematic description of the ASME Section XI Half-Bead Weld Repair Procedure. The cavity (a) is prepared; a butter layer (b) is deposited with a 2.4-mm shielded metal arc (SMA) electrode; one-half of the butter layer is removed (c); and the cavity is again buttered with a 3.2-mm-diam SMA electrode and then filled with 3.2- or 4.0-mm-diam SMA electrodes (d).

Table 1. Summary of Fracture Toughness[a] and Hardness Surveys Across the Various Interfaces in the ITV-8 Half-Bead Weld Repair

Interface Location	Weldment Zone[b]	Fracture Toughness K_{Icd} @ −46°C $MN \cdot m^{-3/2}$	Maximum Hardness (DPH)[c]
Base Metal – Half-Bead Repair	BM	160–230	190
	HAZ	255	290
	WM	100–247	239
Half-Bead Repair – Fabrication Weld	WM	100–247	240
	HAZ	200	230
	FW	40–186	240
Fabrication Weld – Base Metal	FW	40–186	215
	HAZ	∼200	310
	BM	200–220	190

[a] Determined from slow-bend tests of precracked Charpy V-notch specimens.

[b] BM – Base Metal; HAZ – Heat-Affected Zone; FW – Fabrication Weld; WM – Half-Bead Repair Weld Metal.

[c] Diamond Pyramid Hardness.

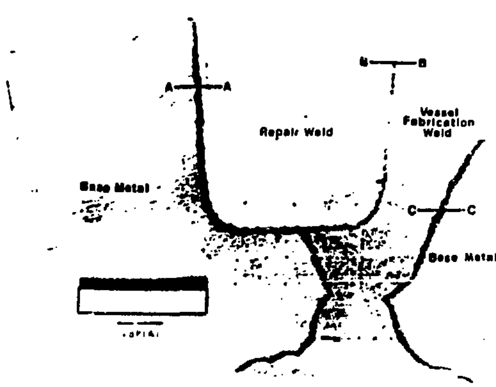

Fig. 2. Location of the weldment zones in a cross section of the V-8 prototype half-bead repair weld in the ITV-8 prolongations. Precracked Charpy V-notch and Diamond Pyramid Hardness tests were made across the weldment interfaces identified as A-A, B-B and C-C.

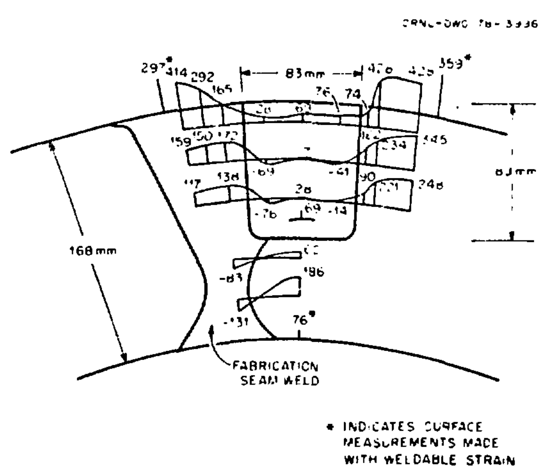

Fig. 3. Circumferential residual stresses (MPa) through the V-8 simulation repair weld.

Table 2. Test Conditions and Results for V-7 Series

Test	Temperature (°C)	Pressure at Leak (MPa)
V-7, Hydraulic	91	147
V-7A, Pneumatic	88	144
V-7B (Weld repair HAZ flaw)	87	152

Table 3. Tensile Properties of Half-Bead Repair Weld Metal for Vessel V-7B

Specimen	Yield (MPa)	Ultimate (MPa)	Total Elongation (%)	Reduction of Area (%)
Test plate	459	565	17.2	71.5
Qualification piece (prolongation)				
V7W67	467	567	14.3	70.8
V7W68	463	578	14.2	72.8