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HALF-BEAD WELD REPAIRS FOR IN-SERVICE APPLICATIONS*

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ABSTRACT

Successful half- or temper-bead technique weld repairs performed to Section XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code guidelines were made to two Heavy-Section Steel Technology Program vessels and a qualification prolongation. Intermediate sized vessels, equivalent in thickness to nuclear pressure vessels, were repair welded and subsequently flawed and pressure tested to approximately 2 1/4 times design pressure before leakage occurred.

Discussed are the standards and procedures used with half-bead repairs, resultant induced metallurgical and stress effects, flaw test criterion, pressure test details and results, and recommendations for further development work for a speedier application process.

Key Words: ASME Code Section XI Weld Repairs; half-bead welding; half-bead weld repairs; HSST vessels, weld repairs; nuclear vessels, weld repairs; pressure vessels, weld repairs; temper-bead welding; temper-bead weld repairs.

PREFACE

The in situ repair of a flaw in a large nuclear pressure vessel could be a complex undertaking. For normal shop fabrication, a thermal stress relief is used to reduce peak welding stresses; however, accomplishing this task under field conditions could result in difficulties related to warpage of the vessel. Consequently, Section XI of the ASME Boiler and Pressure Vessel Code (1) has provided guidelines for making major repairs by welding without a subsequent thermal stress relief. This repair weld procedure employs a technique known as the "half (or temper) bead" technique. In principle, this procedure involves applying each weld pass in such a manner that it tempers the preceding weld pass. Thus, brittle transformation products created during welding will be rendered more ductile. Although this technique is currently used in the repair of petrochemical pressure vessels, a demonstration of the practicality and effectiveness of this repair technique has not yet been made for a full scale nuclear pressure vessel.

The Heavy-Section Steel Technology (HSST) Program conducted by the Oak Ridge National Laboratory (ORNL) and sponsored by the Nuclear Regulatory Commission (NRC) has been pressure-testing deliberately flawed intermediate sized vessels having wall thicknesses of 152-mm (6-in.). One such vessel, ITV-7, contained a deep external surface flaw oriented in the axial direction, and was hydraulically pressurized to failure. Leakage occurred when the vessel was pressurized to 2 1/4 times the design pressure (2). The through-wall flaw was subsequently repaired according to Section XI procedures and the vessel reflawed identically, away from the repair weld. The repaired vessel, redesignated vessel ITV-7A, was pneumatically pressurized to failure, with leakage occurring through the below-flaw ligament at a pressure almost identical to the leak pressure of vessel V-7. No abnormalities were noted in the region of the half-bead weld repair (3). Following another Section XI through-wall half-bead weld repair, this same vessel was once more flawed in an identical manner, except for the location of the flaw in the heat-affected zone of the second weld repair. The vessel, redesignated ITV-7B, when subjected to hydraulic pressurization again failed in the same manner and at nearly the same pressure as in the previous two tests (4).

The half-bead weld repair made in preparation for the V-7A test was performed by Combustion Engineering, Inc., in Chattanooga, Tennessee, and the weld repair made in preparation for the V-7B test was performed by the Westinghouse Electric Corporation in Tampa, Florida. Westinghouse also performed an approximately half-wall thickness Section XI repair to new intermediate test vessel V-8, filling an axially oriented repair cavity centered on one side of the original fabrication seam weld in the vessel's cylindrical section. ORNL developed and administered the repair specifications and procedure qualifications for the work according to Section XI guidelines. Welding was done in the horizontal position for the Combustion work, and in the vertical position for the Westinghouse work. ORNL also performed extensive strain gage monitoring during all phases of the repairs and subsequent flawing, and conducted extensive material-characterization and property tests on the vessels and vessel repair qualification prolongation cylinders. GATX/GARD, Inc., used acoustic emission equipment to observe and record sounds emitted during the ITV-7B repairs without observing any abnormalities.

The feasibility of performing Section XI repair welds was demonstrated for horizontal or vertical vessels. This report documents details of the procedures used in the half-bead weld repairs, discusses resultant metallurgical and stress effects, flaw criterion, pressure test details and results, and offers recommendations for further development work toward a speedier application process for weld repairs.

BACKGROUND

Description of Test Vessel

Intermediate test vessel V-7 represents one vessel in a series of ten vessels produced for the ORNL HSST program. The design of the intermediate test vessels provides for (1) material variation in base material and welding seams, (2) cylindrical shell thickness approximately the same as light-water reactor (LWR) vessels, (3) special head and closure design to give reasonable assurance that these components would not fail prior to failure of the cylinder at the test flaw, and (4) achievement of economy by competitive lump sum bidding.

The general features of the 99-cm (39-in.) outside diam, 15.2-cm (6-in.) wall thickness × 254-cm (100-in.) overall length vessel are shown along with the various weld repair and flawing details in Fig. 1. More detailed design and procurement activities for achieving the foregoing objectives are covered in Ref. 5 and 6. The assembled vessel weighs about 18,300 lbs. Vessel weight less head is approximately 16,400 lbs. Vessels consist of ASTM A508 class 2 forgings for the hemispherical head, the cover closure, and the cover flange and of either A508 class 2 forging or rolled ASTM A533, grade B, class 1 low alloy plate for the cylindrical test sections, the latter being used for vessel V-7. The two prolongations used in conjunction with the two vessel repairs were cut from two vessel cylindrical sections, and were manufactured and heat treated concurrently. Except for vessel V-6, the cylindrical shell courses each contained one longitudinal seam weld. These welds and the two circumferential seam welds joining the head and flange ends were welds made with submerged-arc E8018 NM filler rod. The fabrication sequence consisted of welding, preliminary weld seam ultrasonic inspection, weld repair, conventional post-weld heat treatment, intermediate weld seam ultrasonic inpsection, radiography, hydrostatic testing, final weld seam ultrasonic inspection, magnetic particle inspection, and leak testing.

The V-7 Test

The initial test of ITV-7 was a crack-initiation fracture test in vessel shell plate material with a sharp outside surface flaw 45.7-cm (18-in.) long and about 13.5-cm (5.3-in.) deep, leaving a minimum wall-thickness ligament of approximately 18-mm (0.7-in.) depth for flaw propagation. Flaw location, shape and dimensions are shown in Fig. 1. The vessel was heated to 91°C (196°F) and pressurized hydraulically until leakage through the below flaw ligament terminated the test at a peak pressure of 147 MPa (21,350 psi), a failure pressure equaling 2.2 times design pressure. The vessel, as expected, did not burst. Upon depressurization, the rupture ligament closed so as to maintain static pressure without leakage at about 129 MPa (18,700 psi). The test demonstrated leak without break, at a loading for which the inside surface of the vessel was about to yield, and at a test temperature higher than the Charpy upper-shelf temperature which was chosen to provide toughness in the specimen similar to that in a operating reactor vessel. More complete details of the V-7 test are covered in Ref. 2.

V-7 REPAIRS FOR V-7A TEST

Underlying Information

Vessel V-7A was the first of the intermediate test vessels to be produced by repair of a vessel (Vessel 7) that had been previously tested to the point of failure. Vessel 7 was suitable for further testing because, in the initial test, the vessel had developed a rupture through the wall only immediately beneath the prepared flaw and gross residual distortion and plastic deformation of the vessel was limited to the region of the flaw. Thus distortion did not affect the removal and resealing of the head, or the repair of the flaw itself. After being repaired, vessel V-7 was redesignated V-7A.

The cylindrical test section in regions remote from the flaw had reached strains of 0.29 to 0.47% on the inside surface and about 0.1% on the outside. Permanent set in the vessel prior to weld repair indicated strain distributions of 0.36% on the inside and −0.02% on the outside in the location 135° from the original V-7 flaw which was therefore selected for the V-7A flaw to minimize the influence of residual strain on the V-7A test. The V-7A flaw location, relative to the old flaw, and typical flaw details are shown in Fig. 1.

Weld Repair Program

The original flaw in vessel V-7 was a 25-mm-wide (1-in.) machined trapezoidal shaped notch sharpened by a cracked electron-beam bead. The cross section of the flaw lay in a radial-axial plane of the test section 180° from the longitudinal submerged-arc vessel seam weld. Consideration was given to making a repair of the fracture zone by the most economical means consistent with the objectives of the subsequent test. Alternatively, the vessel could have been repaired by procedures applicable to nuclear vessels. The latter course was chosen, since the test being planned for V-7A would be a rare opportunity to test a repair weldment to a high overload.

A repair weldment was designed for vessel V-7 to utilize the half-bead procedure prescribed by Subarticle IWB-4420, Procedure Number 4, "Welding Low Alloy Steels," of Section XI of the 1974 ASME Boiler and Pressure Vessel Code (1). This procedure is intended to be used for repairing components for which it is impractical to perform the usual post-weld heat treatment at 590 to 630°C (1100 to 1150°F). ORNL Welding Specification No. W-HB-100, based upon this procedure in the Code, was written and issued especially for the repair of vessel V-7 (3).

The welding procedure incorporated in the specifications was developed with the advice of the PVRC Advisory Task Group on Weld Repair of Pressure Vessels, under the chairmanship of E. Landerman of Westinghouse Electric Corporation. The Electric Power Institute (EPRI), as subcontractor to Union Carbide Corp., Nuclear Division (UCCND) under purchase order, had the repair made by Combustion Engineering, Inc., (CE) at no cost to the government. R. E. Smith was project leader for EPRI, and W. D. Goins of CE directed the weld preparations, procedure qualification, repair welding, and nondestructive examination. A detailed account of the work done by CE is given in Ref. 7.

Section XI of the Code requires the preparation of a welding procedure qualification piece similar to the repair weldment. The cylindrical prolongation of intermediate test vessel V-9 was chosen for this purpose, since it was fabricated from the same heat as vessel V-7, whose prolongation had already been cut up for material characterization. Since vessel V-7 was not a "Code" vessel in the strict sense of its future use in fracture tests, the vessel did not demand a Section XI repair. Hence, the procedure qualification piece was not pretested as required by the Code for the purpose of qualifying the procedure used on the vessel; instead, both the vessel and the prolongation were prepared and welded concurrently. The prolongation was eventually sectioned for some material property tests of the type normally required by Section XI, for other material property studies, and for the measurement of residual stresses.

Due to the short length of the prolongation [635-mm (25-in.)], it was necessary to weld restraints on each end, prior to repairs, to simulate the V-7 vessel restraint. 102-mm (4-in.) square carbon steel bars were welded to the ends of the prolongation with shielded metal arc fillet welds, with the prolongation preheated to 149°C (300°F) for this work.

The cavity containing the vessel 7 flaw was enlarged using a conventional manual air-carbon arc process to provide access for manual shielded metal arc half-bead repair welding (8). In the air-carbon arc process, a D.C. arc is maintained between the work piece and a copper coated carbon electrode. The molten material is blown away by high velocity jets of compressed air. The vessel prolongation test piece (V-9 prolongation) cavity was also excavated using the air-carbon arc process, and an oxygen lance (8) was used to pierce a starter hole through the prolongation. Preheat was maintained between 177 and 204°C (350 and 400°F) during lancing and air carbon-arc gouging. The surface intersections of the final air-arc enlarged cavities were rectangles, approximately 102-mm × 495-mm (4-in. × 19 1/2-in.) on the outer, and approximately 9.5-mm × 241-mm (3/8-in. × 9 1/2-in.) on the inner vessel surfaces, and approximately 102-mm × 292-mm (4-in. × 11 1/2-in.) and 9.5-mm × 38-mm (3/8-in. × 1 1/2-in.) on the respective prolongation surfaces. Longitudinal cavity ends were sloped at approximately 130° included angles with the cavity bottom and the sides at approximately 105°.

In order to assure complete removal of the air-arc surface, carburization, and any heat-affected zone resulting from the air-arc process, a minimum of 6.4-mm (1/4-in.) of metal was ground from the surface. Metal removal was gaged by grinding grooves into the cavity walls 6.4-mm (1/4-in.) deep. The cavity was then ground smooth after the grooves were completely eliminated. Liquid penetrant and magnetic particle examinations followed. Final vessel prerepair cavity dimensions are shown in Fig. 1, along with 6.4-mm (1/4-in.) thick steel backing bars which were tacked to the vessel and prolongation inside surfaces.

The prolongation's interior and exterior was instrumented with strain gages adjacent to the repair cavity. In addition, a pair of circumferential gages, one inside and one outside, were placed 180° from the repair cavity. Four outside surface gages were used near the cavity's edges. CE installed thermocouples at each strain gage location to allow for adjustments of apparent strains for temperature. AILTECH type SG 425 (900°F maximum temperature tolerance) gages were used within 5-mm (2-in.) of the cavity and type SG 125 (600°F maximum temperature tolerance) gages for other locations. A total of 6 high temperature and 8 intermediate temperature gages were used. Strain observations were made at several stages of the repair process and were used subsequently in the residual stress study described in Section 5.

Two 11 kilowatt electrical resistance heaters were placed inside the vessel. Channel element resistance heating for the vessel and prolongation were subcontracted by CE to Heat Engineering, Inc., subsidiary of Electric Arc, Inc., heat-treatment specialists, of Cedar Knolls, N.J. The heaters were tack welded to supports placed inside the vessel and welded to the vessel weld cavity backing bar. Two additional units of 1 1/2 kilowatt each were placed in the flange opening to trim and balance the heat flow in the vessel. The prolongation was preheated by placing five 3 1/2 kilowatt heating elements across the end braces. Approximately five hours were required to bring both the vessel and prolongation from room temperature up to the required preheat temperature range of 177 to 260°C (350 to 500°F).

Half-Bead Procedures

Regions of base metal adjacent to a weld are known as weld heat-affected zones (HAZ) because they are heated to a temperature above the lower critical transformation temperature during welding. In any large metal object, a relatively small weld bead cools almost instantly upon deposit. Normally, an elevated temperature postweld heat treatment is performed after welding to temper any transformation products in the HAZ and to relax the weld induced residual stresses. When an elevated temperature postweld heat treatment cannot be performed, as in the case of the vessel V-7 repairs, tempering of the HAZ is performed by controlling the weld heat input from subsequent weld layers and is called the half bead temper procedure. The entire cavity is first "buttered" (covered) with weld metal using a small diameter electrode to produce a shallow, uniform HAZ. Approximtely one-half of this first layer is removed by grinding, thus allowing the heat from a second buttering layer to penetrate and temper any transformation products present in the weld HAZ. A larger electrode is then used for the next weld layer to provide additional heat input for HAZ tempering. The third and remaining layers are deposited using astill larger electrode, where possible, to provide additional tempering of the HAZ. Improved weld rod chemistry is also used to minimize transformation product problems and to blend successive weld deposit layers without inducing significant inter-layer adverse effects.

Welding was accomplished by the manual shielded metal arc process. The weld cavities were "buttered" with 2.38-mm-diam (3/32-in.) electrodes. All welding was done in the flat, or horizontal position mode. Bead sequences started from the inside diameter cutouts, atop the backing bars, first along the short end slopes, then along the longitudinal sloped ends. Initially, one-half of the cavity was buttered with the horizontally positioned vessel rotated for flat position welding. Thereafter, the vessel was then rotated 180° to butter the other half of the cavity. Punched reference gage marks were applied and used for measuring the cavity dimensions before and after buttering. A gage was placed in the cavity and measurements were taken from each side wall reference point to the cavity centerline. Approximately one-half of the buttering layer was removed by grinding and additional measurements were taken after grinding to assure that the remaining weld thickness was appropriate. It proved rather difficult to take accurate, reproducible measurements in the cavity at about 204°C (400°F).

After one-half of the layer was ground off, the cavity was inspected by magnetic particle (MT) examination and then a second weld layer was deposited over the cavity surface using a 3.18-mm-diam (1/8-in.) electrode. The vessel rotation and weld bead sequences used for the second layer were the same as for the first. Bead starts, however, were staggered from the initial passes. After the second layer of buttering was completed and MT inspected, the cavity was rotated to the 12 o'clock position and the welding completed using 3.18-mm-diam (1/8-in.) and 3.97-mm-diam (5/32-in.) coated electrodes. The first bead deposited in each vertical layer was placed next to the cavity side wall and the subsequent beads were sequenced inward toward the center of the cavity. MT inspection was performed on alternate layers and on the final ground layer. There were no MT indications detected in either cavity at any inspection point.

CE took special precautions to keep the electrode moisture level as low as practical to reduce the possibility of hydrogen delayed cracking. Postweld X-ray and ultrasonic examinations (UT) showed no indications of any such cracking. All coated electrodes were baked in accordance with the time-temperature parameters specified in paragraph IWB-4423(3)(d) of Section XI of the ASME Code (1) and then the electrodes were placed in sealed vacuum packages. After removal from the vaccum packages, the electrodes were placed in portable heating ovens operating in the temperature range of 107 to 149°C (225 to 300°F). Electrodes left in a portable oven for over an hour were discarded. Electrode samples were periodically removed from the portable holding ovens and the moisture in the coating was measured using the moisture test specified in paragraph 25 of SFA-5.5, "Specification for Low Alloy Steel Covered Arc-Welding Electrodes," ASME Code Section II (9). The results of these overchecks were compared with the 0.08% maximum moisture level in the electrode coatings prior to vacuum packaging. Highest moisture determination was 0.14%, about a factor of three less than the 0.4% maximum specified for this type of work.

After the welding was completed, the weld surface was ground smooth while maintaining the temperature in the range of 177 to 260°C (350 to 500°F). The final ground surfaces were reinspected by MT examinations and the welds were then heated in the temperature range of 232 to 288°C (450 to 550°F) for four hours. The temperature of the vessel and prolongation repair welds were controlled within ±11K (±20°F) of the vessel average temperature at all times. The heatup and cooldown rates were approximately 14K (25°F)/hour. Finally, the backing bars were ground from the vessel ID's using a pole grinder. The final ground inner surfaces were MT inspected using an AC yoke so as not to leave prod marks on the final ID weld surfaces.

The entire weld and 1/2T of adjacent base metal of both the vessel and prolongation were examined ultrasonically in accordance with the requirement of paragraph IWA-2232 and Appendix I of Section XI (1). The required examination was performed three times: (1) as soon as the vessel and prolongation surfaces reached room temperature; (2) 48 hr after both surfaces returned to room temperature; and (3) approximately 4 weeks later. There were no recordable indications detected during any of these inspections.

Radiographic examination was performed with a 7 1/2 MeV Varian linear accelerator and Kodak "M" film in accordance with the requirements of paragraph IWA-2231 of Section XI (1). No major defects were found in the vessel weld, but minor porosity was detected near the inside surface of the weld in the prolongation. It is believed that this porosity was caused by the restricted access available to the welder in the deep, narrow portion of the cavity.

To provide sufficient material for characterizing the properties of the weld metal, two additional test plates were also welded and heat treated, using the same parameters that were used to repair the vessel. MT examination and radiography revealed no rejectable indications in these plates. The base material in these plates came from the 3/4T depth of section 02FH of HSST plate 02 (10,11), a plate quite similar to the A533 plate sections of the vessel and prolongation.

Repair Weld Characterization

The welding procedure qualification prolongation and one of the two weld metal test plates prepared by CE were used for characterizing the properties of the weld repair zone and for investigating the through-the-thickness residual stress in the weldment. Ultimate and yield stresses, Charpy impact energy, and lower bound (equivalent energy) fracture toughness measurements of the weld metal were made.

V-7A test plate (weldment W-1 repair weld material) tensile test results, for the W orientation (axis perpendicular to the welding direction and parallel to the plate surface) and for the temperature range from −73 to 177°C (−100 to 350°F), are shown in Fig. 2. Charpy V-notch specimens, with the notches located at the weld centerline, were tested in the WL orientation (axis as in the tensile specimen, crack propagating in the weld direction). Charpy V-notch impact properties are given in Fig. 3. Precracked Charpy specimens of the same orientation were also tested statically with the results shown in Fig. 4. The fracture toughness and hardness data proved to be very similar to the results from the V-7B repair, hence these are discussed in Section 4 of this report. Detailed accounts of the V-7A repair characterization studies are given in Chapter 3 of Ref. 3.

V-7A Test Summary

The V-7A (weld repaired vessel) test was generally a repeat of the initial V-7 test, with identical flaw preparations in a base metal region of the vessel cylinder, and a vessel test temperature of 91°C (196°F), except that pneumatic pressurization was used instead of hydraulic pressurization. The V-7A test was a sustained load test lasting for a period of approximately 80 hours, compared with 2.2 hours for the V-7 test. The V-7 test is fully described in Ref. 2 and the V-7A test in Ref. 3.

The V-7A test also terminated with leakage through the flaw's remaining ligament, at a test pressure of 144.2 MPa (20,920 psi), which was only about 1% above the predicted rupture pressure and slightly less than 2% below the original V-7 leak pressure of 147 MPa (21,350 psi).

During the V-7A test crack growth in the remaining ligament became noticeable at about 115 MPa (16,700 psi). Axial crack extension was negligible below 138 MPa (20,000 psi). Before the final maximum pressure was reached, there were ultrasonic indications of about 9 mm (0.35 in.) of axial extensions from each end of the flaw. Acoustical emission monitoring recorded several events during the test. Emissions were detected from both ends of the flaw and from the longitudinal (fabrication) weld of the vessel's cylinder. The halfbead weld repaired zone was quiet. Strain measurements on the weld repair inner surface zone indicated that yielding began there only well above design pressure [66.9 MPa (9710 psi)], when considerable yielding had already occurred in other unflawed parts of the test vessel cylinder. In evaluating the nonlinear behavior of the weld repair itself, one must not only account for the residual stresses produced by the repair itself, but also the residual stress field in the large region around the repair as a result of the original V-7 test.

A wedge specimen containing the fracture surfaces of the flaw region was removed from V-7A after the pneumatic sustained-load test. The specimen was chilled in liquid nitrogen, split in a press-brake, and examined by light microscopy and scanning electron microscopy. The fracture surfaces of the flaw region formed during the test have a dimpled morphology that is characteristics of cracks extended by ductile tearing. Posttest ultrasonic examinations of the weld repair areas revealed no irregularities.

V-7A REPAIRS FOR V-7B TEST

General Information

Following the V-7A test, vessel 7 remained suitable for further testing, because, as in the earlier two tests, the vessel had developed a rupture through the wall only in the general vicinity of the prepared flaw and gross distortion and plastic deformation of the vessel was limited to this region. Permanent strain encountered in this region approached 1% on the vessel's inner surface, and 3/4% on the outer surface. Permanent strain at the boundaries of the subsequently prepared cavity for V-7B half-bead weld repairs was on the order of 50% of those values.

A through-wall wedge piece, approximately 114-mm wide × 527-mm long (4 1/2-in. × 20 3/4-in.) containing the V-7A flaw was removed from the vessel by air-arc gouging for detailed study of crack propagation. Both ends of the wedge cutout cavity were gouge-tapered at 112° (head end) and 142° (dome end) included angles for a 768-mm-long (30 1/4-in.) vessel top surface cavity opening. Cavity sides were cut on radial surface planes. Thereafter, an additional 6 to 8 mm (1/4 to 5/16 in.) of material was removed by grinding or milling along and adjacent to the cutout's boundary surfaces to eliminate flame induced carburization and heat-affected zones. Machine milling was selected along the radial plane surfaces of the longitudinal cavity edges to establish accurate reference planes for flawing within the center portion of the heat-affected zone of the vessel V-7A weld repair for the V-7B test. The main objective for the V-7B test was to demonstrate the structural integrity in the upper shelf temperature range of a vessel containing a large flaw in the heat-affected zone of an inservice repair weld. The preweld repair cavity is shown in Fig. 1.

Weld Repair Program

Westinghouse Tampa Division (WTD), under contract to UCCND, ORNL (Contract UCCND P.O. 75Y13494V), used in "Half-Bead Temper Welding Technique" to weld repair two intermediate test vessels and one cylindrical prolongation, with all of the

HSST Program vessels being placed in the vertical position. The contract work also included preliminary practice and familiarization half-bead welding on similar wall thickness test plate and weld coupons. Tensile test plates were also furnished to ORNL for analysis, with results quite similar to the CE findings reported earlier for the V-7 work.

WTD's repairs involved previously used vessel V-7A, new (untested) vessel V-8, and a new prolongation to qualify procedures for both vessel repairs. WTD's preparations for the V-7B test included removal of the V-7A vessel flaw zone and preparing the appropriate through-wall cavity boundaries for half-bead repair welding, as well as similar cavity preparations on prolongation V-8. The vessels and respective cavity details are shown in Fig. 1. The prolongation consisted of an open-ended cylinder which was manufactured from the same heat, and given the same heat treatment and stress relief as vessel V-8. The prolongation had two test areas located 180° apart, one with a through-the-wall cavity similar to the cavity in vessel V-7B, and the other, with a cavity about half-way through the wall similar to the cavity in vessel V-8. The half-wall-thickness cavities had been premachined into the longitudinal seam welds of both vessel V-8 and the V-8 prolongation by UCCND.

Post repair weld machining and flawing of vessel V-7B centered in a longitudinal heat-affected zone of the weld repair and of vessel V-8 in a high residual stress and low-toughness zone. These preparations and pressure testing were to be accomplished later at ORNL. Details of the vessel V-8 post repair weld program activities are pending and will be reported in the future. The prolongation was destructively tested at ORNL to determine mechanical, physical and structural properties of the weld repairs, and thereby also served to qualify WTD's welding procedures.

152.4-mm (6-in.) thick (ASME SA533, grade B, class 1) material was stringer-bead welded for each of the repairs in the vertical position using 2.4-mm-diam (3/32-in.) Type 8018-C3 electrodes for the first layer and 3.2-mm-diam (1/8-in.) for subsequent passes and for completing the weld. Electrode coating inspections and electrode moisture content controls were specified and adhered to. All layers of weld were staggered whenever physically possible; starts and stops and corner deposits contained within a layer were in-line to facilitate subsequent grinding.

Air-arc gouging cavity preparations and all welding repair work was done with the vessels preheated to 177–204°C (350–400°F). Preheat and postweld heating operatins were performed by the Cooperheat Company,[1] under subcontract to WTD, using resistance heaters of the flexible ceramic pad type which were attached to the vessel interior. Ceramic fiber insulation was used on the vessel exterior surfaces. Thermocouples were used to control and monitor temperatures over a 3T [T = 152 mm (6 in.) = vessel wall thickness] zone beyond cavity boundaries. Preheat temperatures in the repair zones were maintained within the temperature range of 177 to 260°C (350 to 500°F) throughout all work. Temperatures were not allowed to fall below 177°C (350°F) until the completion of either an interval postweld heat treatment (PWHT)[2] of 260°C ± 28°C (500°F ± 50°F) for 1/2 hour, or after a final PWHT at the same temperature for 4 hours.

Vessel V-7B longitudinal cavity surfaces had been premilled by UCCND to establish final and optimum planes for subsequent postweld repair heat-affected zone flaw preparations. WTD's layout for gouging the top- and bottom-end cavity boundaries (and the entire V-7B prolongation cavity) allowed for 6.4-mm (1/4-in.) grindoff in order to ensure complete removal of the air-arc surface carburization as well as any heat-affected zone resulting from the air-arc process.

Routine magnetic particle inspections were conducted for each of the first three weld passes; thereafter, on alternate passes. Final nondestructive repair inspections were held a minimum of 48 hours after the vessels had cooled to ambient temperature. Magnetic particle

1 Cooperheat Company, Cooperheat Eastern Division, 955 East Hazelwood Ave., Rahway, New Jersey 07065.

2 PWHT actually infers a postweld tempering treatment only.

surface inspections and ultrasonic inspections of the repairs revealed no indications of delayed cracking. A repeat ultrasonic inspection to one of the vessel cavity repairs by ORNL, approximately twelve weeks after repair welding, also revealed no delayed cracking indications. Final ultrasonic and radiographic test results were acceptable for all repair welds.

GATX/GARD, Inc.,[3] used acoustic emission equipment to record sounds emitted during welding. No significant or rejectable indications were identified. Strain gage instrumentation to record weld-operation-induced residual stresses was attached for the repair operations and was monitored by ORNL personnel.

WTD encountered some difficulties in the execution of the half-bead technique weld repairs: (1) the determination of how to measure or judge when half of the butter-layer was ground off, (2) welding with 4-mm-diam (5/32-in.) coated electrodes in the vertical position, (3) porosity formations especially in weld start and stop and in backing plate sloped end boundaries, and (4) problems of limited or restricted access for the welder to reach bottom areas of a through-wall repair.

1. The determination of when the first or "butter" layer has been ground off ends up as a judgment decision. It is extremely difficult to establish accurate reproducible depth measurements in a repair cavity at 177 to 204°C (350 to 400°F). Additional development work is suggested to test alternate techniques toward achieving proper tempering effects to the "butter" layer. Care can be exercised not to grind off the entire layer. Actual ground layer measurements, thereafter, should not be required. The use of small electrodes for the buttering layer followed by a second buttering layer applied with a larger diameter electrode may achieve adequate tempering to the initial layer and the adjacent base metal. It may even be possible to omit grinding for the first layer altogether.

2. Even though CE encountered few problems using 4-mm-diam (5/32-in.) electrodes when welding in the horizontal position, WTD welders welding vertically reported that after burning a 4-mm (5/32-in.) electrode for about 76 mm (3 in.), the remainder of the electrode overheated and hence could not be used. It was also noted that the immediate area being welded overheated, resulting in excessive undercut occurrences. Attempts were made to reduce the heat input to the electrode. Lowering the welding amperage, however, made it extremely difficult to maintain an arc; hence it was decided to complete the welding operations using 3.2-mm-diam (1/8-in.) electrodes exclusively. It is important to note that Westinghouse welders required 62 total layers to fill the V-7B cavity, compared to a 68 layer fill by Combustion Engineering welders for the equally deep V-7A cavity. WTD welders welding vertically apparently progressed at a slower rate, depositing more metal per pass than the CE welders, who when welding horizontally, deposited less metal per pass, even though using a larger electrode.

3. Precautionary measures to stagger weld layers and to contain starts and stops within a layer (and at the corners) in-line for ready grindout did not eliminate porosity formation problems entirely. Despite continuous acoustic emission surveillance and alternate pass magnetic particle inspection, some porosity formed in these locations and remained initially undetected. Such porosity formations were generally of extremely small size and settled in unstacked arrays to be passable under Code specified acceptance provisions. Polished cut slices from the prolongation welds revealed and confirmed such scattered porosity presence. Some problems were also encountered with the fitup of two stacked and contoured 3.2-mm (1/8-in.) backing bars for the cavity bottom. Two bars were chosen for WTD repairs to eliminate time consuming postweld bar grindout, based on CE is work experience during which only a single 6.35-mm (1/4-in.) backing bar was used. The inner backing bar distorted and separated from the outer bar, resulting in a gap, which in some cases was easy to burn through.

4. Limited access hampers manual repair welding efforts, especially for vertical position welding. By comparison,

3 GATX/GARD, Inc., 7449 North Natchez Ave., Niles, IL 60648.

welding the half-wall thickness cavity in the prolongation and in vessel V-8 did not present unusual welding problems because, for these repairs, the maximum welding depth was limited to 89 mm (3 1/2 in.). The welders had sufficient working room to afford easy access to the entire bottom of the repair area. The through-the-wall 155-mm (6-in.) repair cavities in both the V-8 prolongation and in vessel V-7B, however, presented considerable problems for the welders. Their primary difficulties were that of limited access for welding, the 152-mm repair depth, the narrowness of the area to be repaired, and the 7 1/2° angles on each of the cavity's side walls. Deep vertical repair welds which are to be done manually should have greater access for welders which can be provided by using a larger wall angle. It should be noted, however, that "through-wall" repairs are not permitted under Code rules, hence, in "real life" it is quite unlikely that problems of this nature will occur. The V-7A and V-7B vessel repairs were selected to produce extreme conditions. Where such repairs withstand subsequent pressure testing, confidence can be gained for repairs of lesser depth as may be required in operating facility work.

ORNL/NUREG-TM-177 report (12) provides complete chronological listings, job photographs, and discussions of all the half-bead weld repairs and related work performed by WTD during late January and early February 1977.

Repair Weld Characterization

Hardness investigations. A typical microhardness traverse taken across the base metal-repair weld HAZ of the V-7B prototype half-bead repair weld in the V-8 prolongation is shown in Fig. 5, which indicates that the highest hardness values occur in the dark etched 2.29-mm (0.090-in.) wide region which is the heat affected zone. The highest DPH value, 314 (R_c 31.6), occurs twice with a distance of 0.254 mm (0.010 in.). This is in agreement with hardness data obtained from three traverses across a similar HAZ in the V-7A prototype weld in the V-9 prolongation.

Fracture toughness investigations. Static fracture toughness (K_{Icd}) results were also obtained using precracked Charpy-V specimens with the fatigued precrack tips located in the base metal, in the HAZ, and in the weld metal of the V-7B prototype and V-8 half-bead repair weldments made in the V-8 prolongation. Both the 66 to 121°C (150 to 250°F) and the −18 to −101°C (0 to −150°F) temperature ranges were investigated for the V-7B simulation weld, and the latter only for the V-8 simulation weld, because these temperatures bracketed the proposed test temperatures for vessels V-7B and V-8 respectively.

Static fracture thoughness (K_{Icd}) results from the V-7B weldment specimens tested indicate a range from 115 to 301 MPa $\sqrt{m}$ (105 to 274 ksi $\sqrt{in.}$) at −46°C (−50°F), both extremes occurring in the repair weld metal. In the 66 to 121°C (150 to 250°F) temperature range, the K_{Icd} values ranged between 219 to 382 MPa $\sqrt{m}$ (199 to 348 ksi $\sqrt{in.}$). The highest toughness values occur in the base metal-repair weld HAZ and the lower values in the repair weld metal.

The static fracture toughness tests from the V-8 weldment specimens indicate a range from 44 to 366 MPa $\sqrt{m}$ (40 to 333 ksi $\sqrt{in.}$) in the −18 to −101°C (0 to −150°F) temperature region. The lowest K_{Icd} values were obtained from specimens removed from the original prolongation fabrication weld metal and the highest values were obtained in the base metal-repair weld HAZ. In the repair weld, the lower K_{Icd} values occur adjacent to the HAZ (in the weld metal) and the highest K_{Icd} values occur in the fabrication-repair weld HAZ. All of the values that fell below 110 MPa $\sqrt{m}$ (100 ksi $\sqrt{in.}$) were obtained in the original prolongation fabrication weld. Also, the repair weld metal and the HAZ appear to be as tough as or tougher than the vessel base metal.

V-7B Test Summary

The V-7B flaw was again identical to the flaws in the earlier two tests, but was placed centered in the heat-affected zone of the second weld repair. Vessel V-7B was tested hydraulically at about the same temperature, 87°C (188°F), as in V-7 and V-7A. At a peak pressure of 151.8 MPa

(22,020 psi) a leak developed through flaw's remaining ligament as in the previous two tests. All evidence evaluated to date leads to the conclusion that the flaw in V-7B had a residual crack opening of from 9 to 11 mm (0.35 to 0.45 in.) and was tearing nearly unstably but still slowly, beginning in the plane of the original flaw and extending along either edge (parent metal and weld metal, respectively) of the HAZ, frequently crossing through the zone at approximately right angles. The entire crack remained alongside the HAZ.

Post-test conventional ultrasonic examinations of a wedge removed from the vessel and containing the repair weld, machined slot and flaw — from the outside surface — detected a crack at a rejectable level outside the ends of the cavity, at amplitudes between 20 and 63% of the reference level. More sophisticated UT schemes noted that the cracks extend approximately 80 and 160 mm (3 and 6 in.), or even slightly more, from the respective slot ends. Radiography showed that the UT detected cracks are of a ragged nature, which could account, in part, for the generally low amplitudes of some of the UT indications. Slices cut from the wedge confirmed the presence of a crack alongside one side or the other of the HAZ of the repair weld, extending about 80 mm (3 in.) beyond each end of the 457-mm-long (18 in.) trapezoidal slot opening. More detailed test results will be published in Ref. 4.

RESIDUAL STRESSES

General conclusions from residual stress measurements in the vicinity of the half-bead weld repairs made to the vessels and prolongations are:

1. Low tensile and compressive circumferential and axial residual stresses existed in the repair weld metal;

2. The metal adjacent to the weld repairs had tensile residual stresses close to the yield stress;

3. The highest tensile residual stresses in the metal adjacent to the repair welds tended to occur at distances of approximately 25 to 50 mm (1 to 2 in.) from the heat-affected zone.

Residual stresses were determined from pre- and post-weld strain gage measurements and (on the prolongations) from measurements using a semidestructive procedure known as the hole-drilling method. Prolongation specimens were sectioned to expose radial planes through each weld. Through-thickness residual stresses based on hole drilling type measurements, including corrections for sectioning, were in general agreement with the surface strain gage stress determinations.

With regard to residual stress measurement techniques, it was noted that:

1. The hole drilling technique for measuring residual stresses is versatile and effective. A compensation for fictitious stresses that are introduced by drilling should be employed when a mechanical drill is used.

2. Cutting or grinding on surfaces that are to be used as sites for hole-drilling type residual stress measurements can cause misleading results. Controlled gradual removal of surface material can be a very effective means for reducing or eliminating these spurious skin effects.

Complete residual stress discussions for these half-bead weld repairs, including illustrations and stress values, are published in Ref. 13.

HALF-BEAD WELD REPAIR PRODUCTIVITY STATISTICS AND COMMENTS

Half-bead weld repair productivity is extremely slow for all repairs. Comparing half-bead weld repair time compilations from CE (horizontal position mode) and WTD (vertical position mode) work at like cavity depth and compensating for cavity weldup volumes, one notes:

1. More than double time is required for vertical work.

2. Reduced-size through-wall prolongation "practice" repairs offer serious welder access problems, hence take longer to complete.

3. Based on actual arc time, large volume vessel repairs progressed at fill rates of 150 cu cms/hr (9.1 cu in./hr) for horizontal-mode welding, and at 79 cu cms/hr (4.8 cu in./hr) for vertical work. Fill rates for the smaller sized prolongation through-wall cavities were 58% and

75%, respectively, slower. Rates for vessel half-wall-thickness vertical cavity repairs were equivalent to through-wall vertical repairs on the prolongation.

4. Actually, however, arc time realistically amounts to only 33% of welder clocktime for vertical-mode welding, and 50% of clocktime for horizontal-mode work. Productivity based on welder at station time, therefore, is about 1/3 to 1/2 of the stated rates. Combining these numbers with an estimate of two welders per shift to permit continuity of progress, and allowing for rest breaks, etc., plus time for an approximately half-time inspector, and the resultant productivity, based on personel assigned (actual manhours expanded on job), amounts to only 20% and 13 1/3%, respectively, of the initially stated rates.

Even though half-bead work offers an adequate and successful means of repairing vessels without conventional PWHT needs, the execution requirements call for many welder and inspector hours. If such work were to become necessary for a nuclear system component in the presence of a radioactivity background which limits operator exposure time, many people would have to be trained and qualified. Additional research and development work should be sponsored to reduce the time required for such a repair, or to combine features of the process, or a modified process, with accelerated, perhaps automated, or semi-automated final welding methods.

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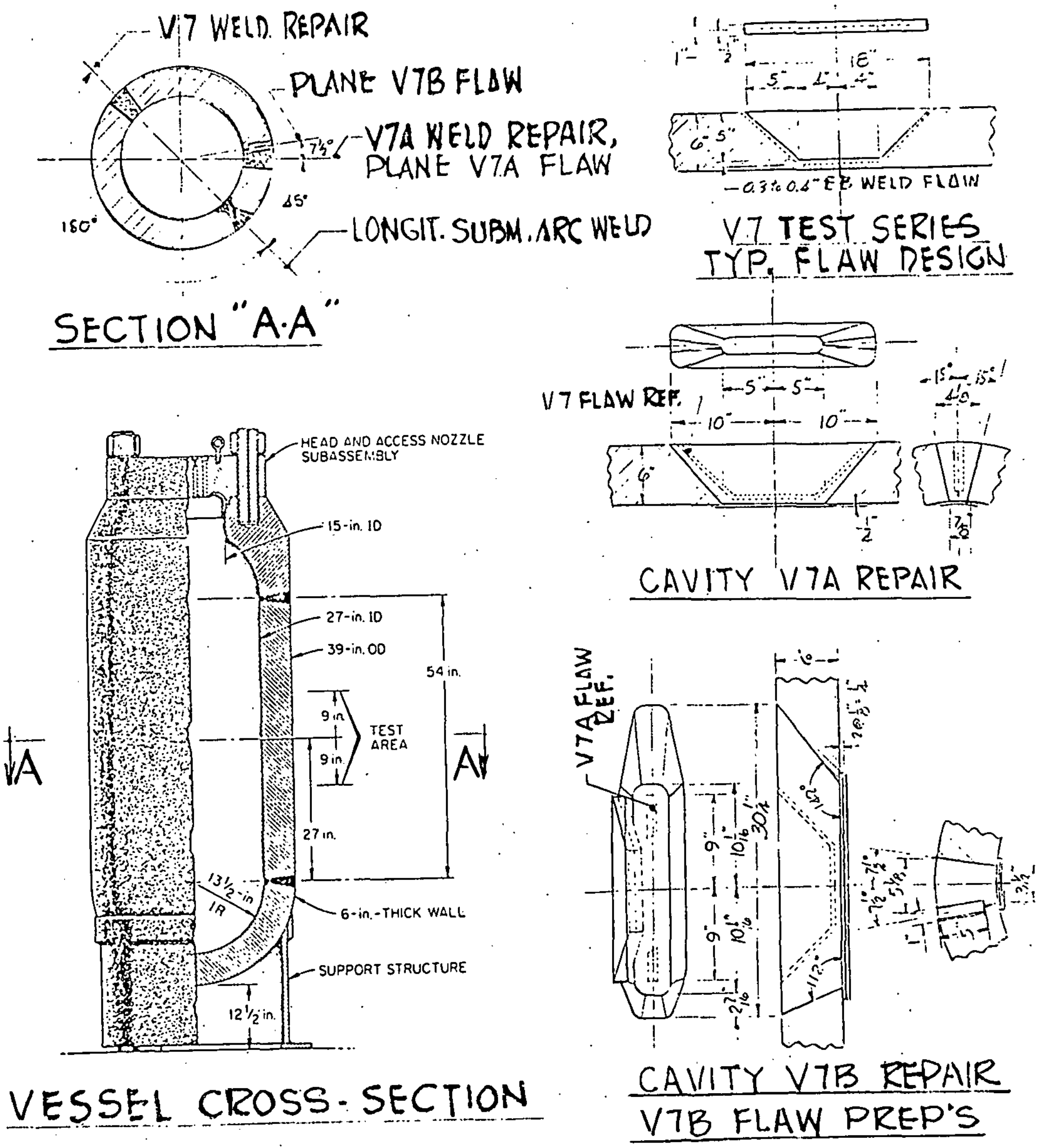

FIG. 1 INTERMEDIATE TEST VESSEL 7

1 in = 25.4 mm

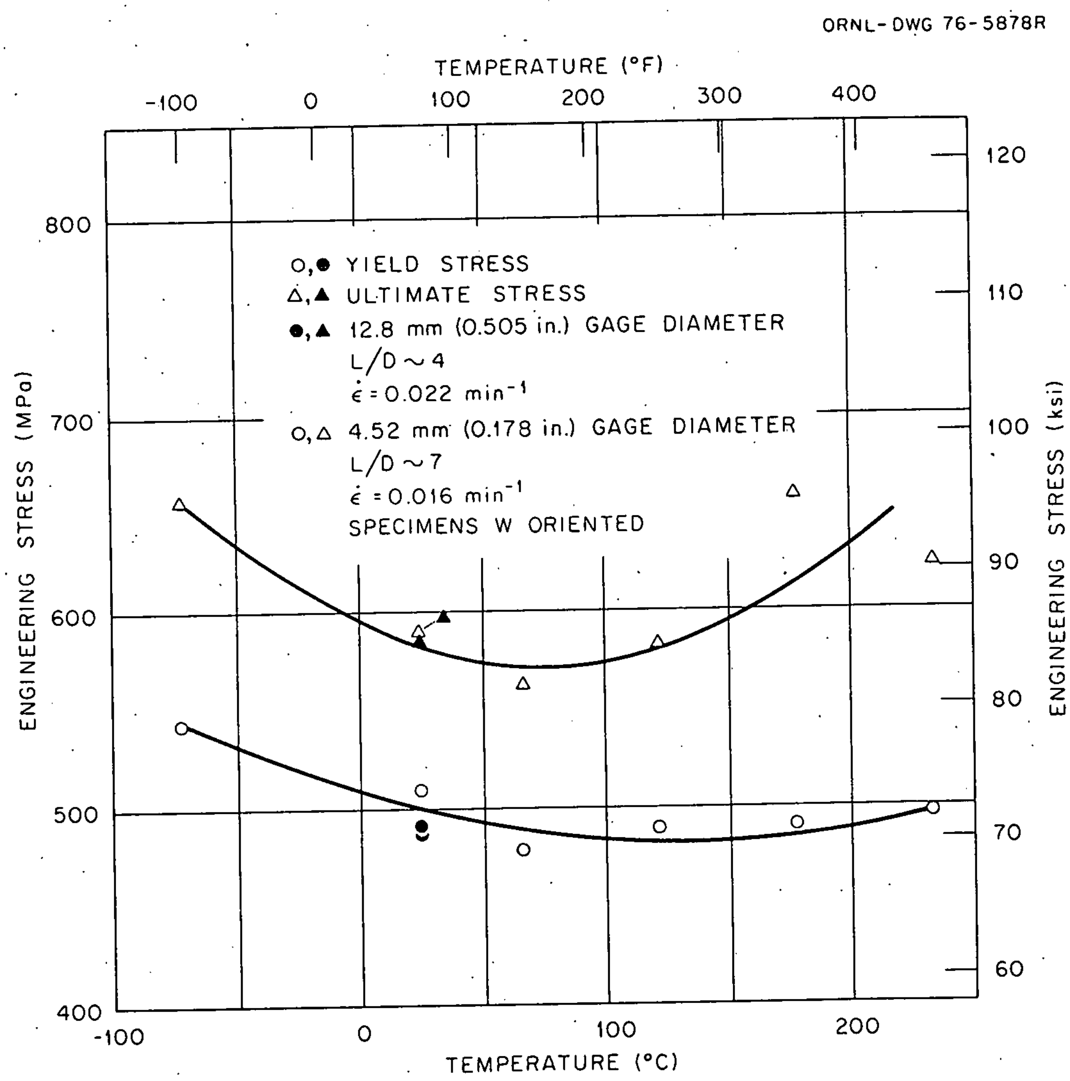

Fig. 2. Variation of tensile properties with temperature for half-bead test weldment W-1 in weld metal.

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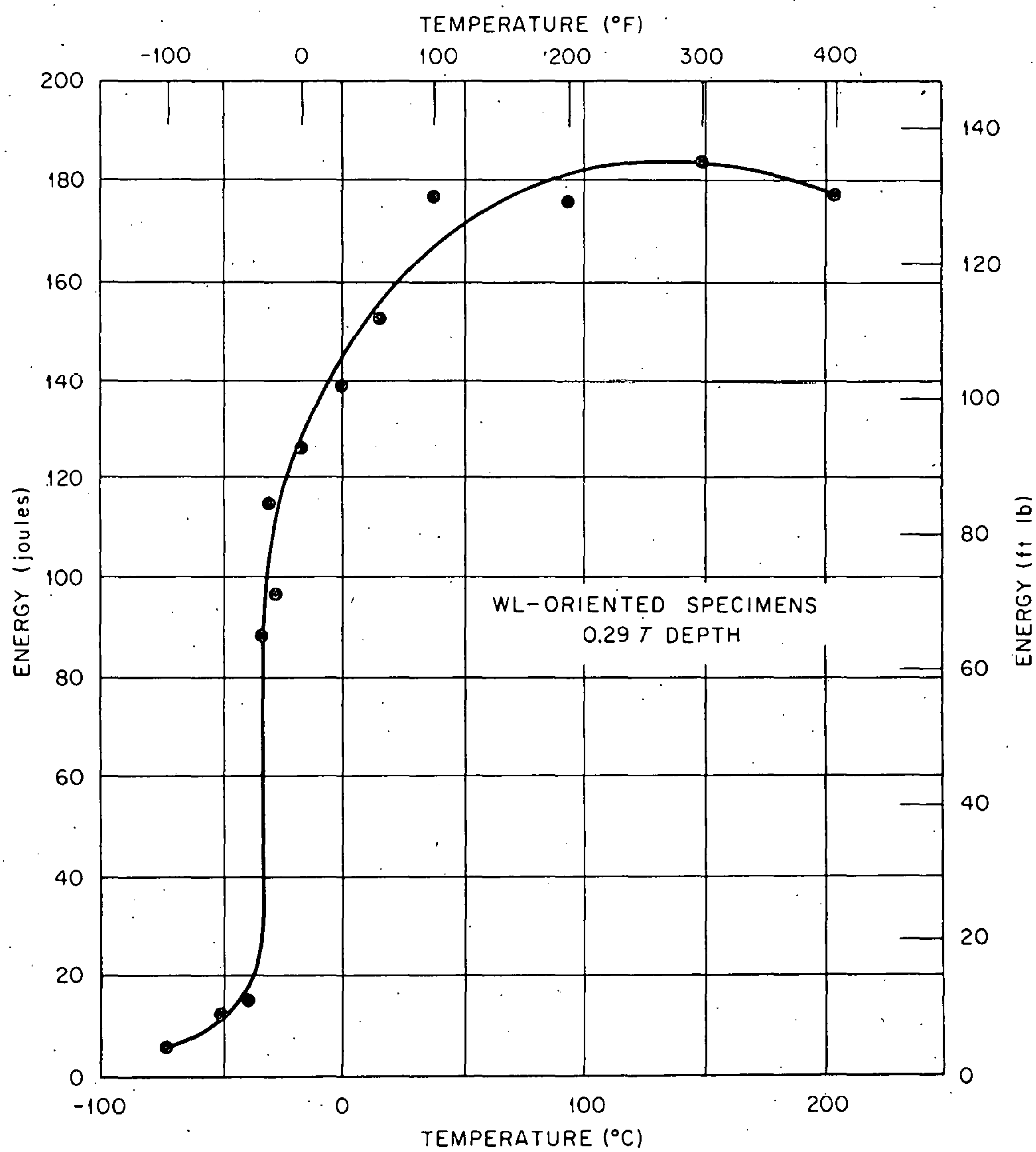

Fig. 3. Variation of Charpy V impact energy with temperature for half-bead test weldment W-1 in weld metal.

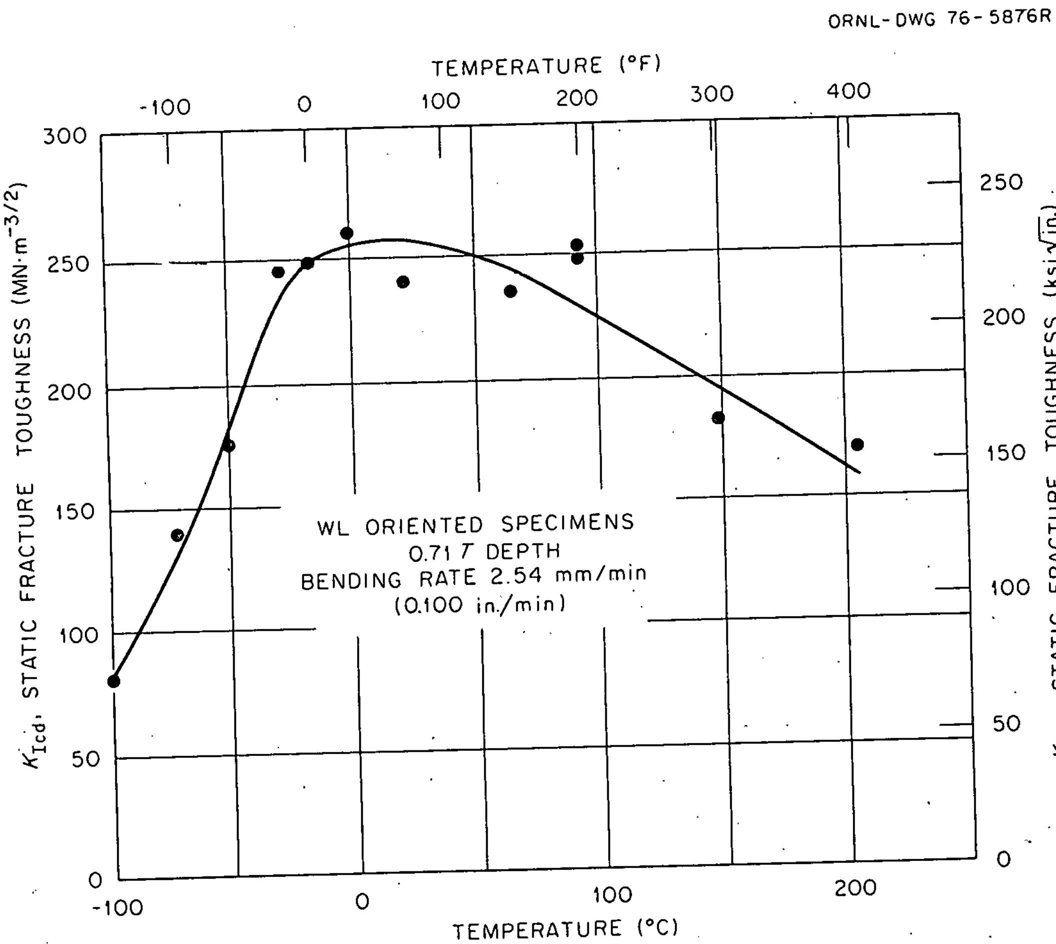

Fig. 4. Variation of fracture toughness with temperature as determined from slow bend tests of precracked Charpy specimens from half-bead test weldment W-1 in weld metal.

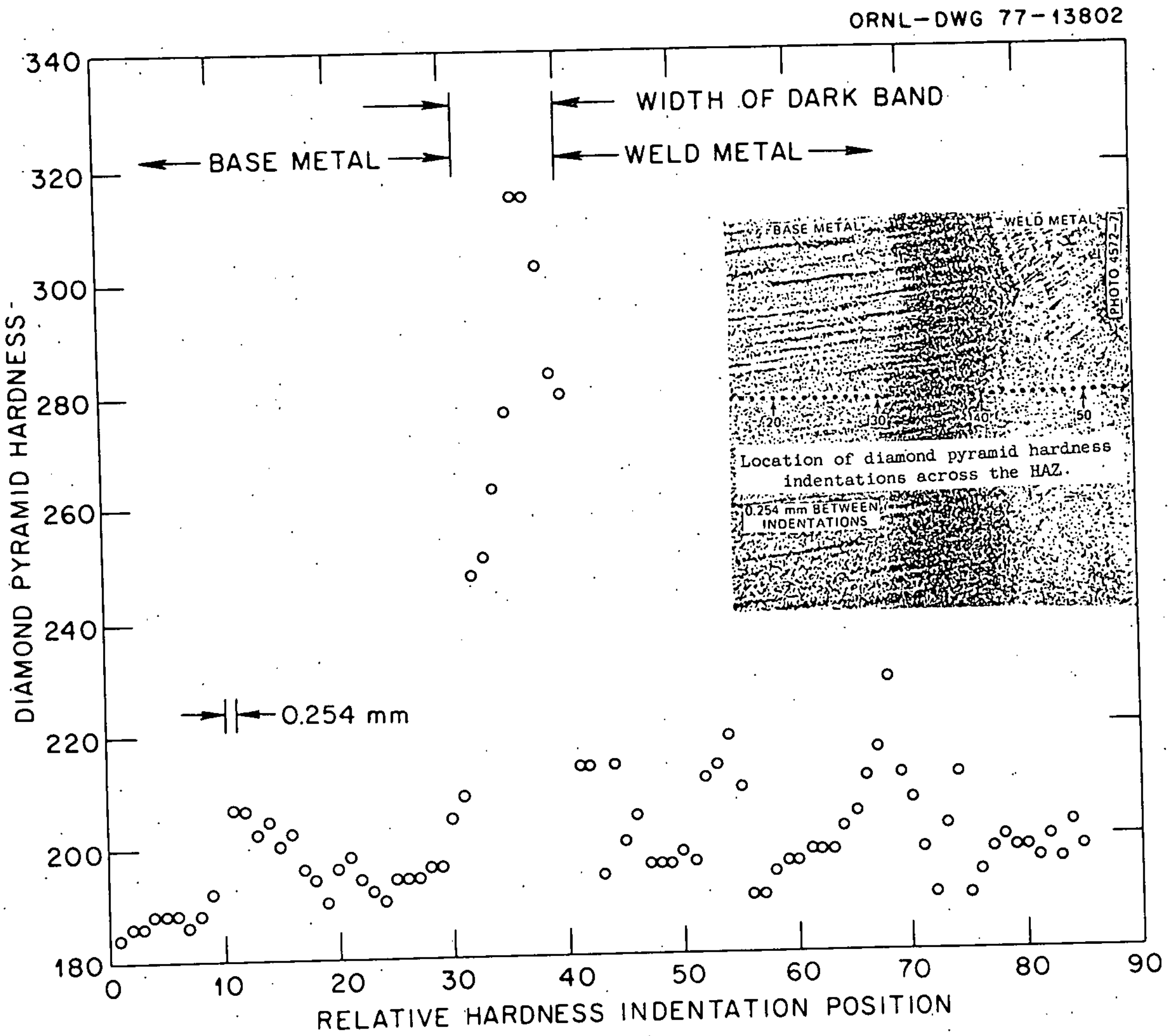

Fig. 5. Hardness traverse of the heat-affected zone and adjacent areas of a cross-section of the V-7B prototype shielded-metal-arc half-bead weld repair in the V-8 prolongation. (Insert — location of diamond pyramid hardness indentations across the HAZ.)