MASTER

TEST OF THICK VESSEL WITH A FLAW
IN RESIDUAL STRESS FIELD*

R. H. Bryan P. P. Holz
S. K. Iskander¹ J. G. Merkle
 G. D. Whitman

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

Intermediate test vessel V-8, a 152-mm-thick vessel fabricated of SA533, grade B, class 1 steel, was pressurized to failure at -23°C. The vessel contained a fatigue-sharpened notch adjacent to a half-bead weld repair that had not been stress relieved. Residual stresses and fracture toughnesses were determined before the pressure test by measurements on a prototypical weld, and fracture predictions were made by linear elastic fracture analysis. Predictions agreed well with test results, demonstrating the important influence of high residual stresses on fracture behavior.

INTRODUCTION

Section XI of the ASME Boiler and Pressure Vessel Code prescribes a procedure that may be used for a repair of a pressurized component after the final post-weld heat treatment when it is impractical to perform another high-temperature heat treatment. This procedure, which employs the half-bead weld repair technique, is used in repairing new components and may be used for repair of pressure vessels and other nuclear components in service. In each

* Research sponsored by Office of Nuclear Regulatory Research, Nuclear Regulatory Commission under Interagency Agreements 40-551-75 and 40-552-75 with the U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering the article.

¹ Computer Sciences Division, Union Carbide Corp., Nuclear Division.

situation in which a repair without post-weld heat treatment is considered, the adequacy of the weldment with regard to expected residual stresses and fracture toughness should be assessed.

In the Heavy-Section Steel Technology (HSST) Program six half-bead weld repairs were made substantially in accordance with Section XI of the Code in 152-mm-thick vessels and cylinders fabricated of ASTM A533, grade B, class 1 steel plates; material properties were determined; residual stresses were measured; and flawed vessels were tested to failure in order to provide baseline information for use by persons who make assessments of such repairs. Four of the welds were within the plate material and extended completely through the wall. Two half-thickness welds were made in regions joining both plate material and submerged-arc fabrication welds. The weldments in the cylinders were prototypical of three different repair welds in the HSST intermediate test vessels V-7 and V-8.

Three tests were conducted with the repaired and flawed vessels. The first two tests, V-7A and V-7B, were performed at upper shelf temperatures. The V-7A test [1] was a pneumatic test with the prepared flaw remote from the repair weld, which was incidental to the test objective. In V-7B [2] the sharpened tip of the prepared flaw was placed in the heat-affected zone of the repair weld. This hydraulic test was an attempted replication of the two earlier tests of this vessel, and it resulted in a leak at about the same pressures attained previously. The flaw in the repair zone, unlike the others, exhibited much greater tearing axially than had been previously observed. This tearing could have been a consequence of the residual stress field near the flaw or of the slightly higher test pressure, which was about $2.2 \times$ design pressure.

The objectives of the test of vessel V-8 were (1) to demonstrate the behavior of a flaw in the residual stress field near a half-bead weld repair, and (2) to evaluate linear elastic fracture mechanics as a means of predicting the combined effects of residual stress and pressure stress on fracture. In order to realize the second objective it was necessary to attain a low toughness condition in a region of high residual stress.

DESCRIPTION OF VESSEL

The 990-mm-OD by 152-mm-thick cylindrical test section of vessel V-8 was fabricated of ASTM A533, grade B, class 1 steel plate. A repair weld 318 mm long by 89 mm deep was made in this cylinder to provide a flaw site in the vicinity of the repair weldment that was not stress relieved. The weld was made in accordance with the sequence prescribed in the ASME Boiler and Pressure Vessel Code, Section XI, Subsubarticle IWB-4420, weld repair procedure without post-weld stress relief. [3] A flaw was machined and fatigue sharpened in the original vessel fabrication weld, as shown in Fig. 1.

The Westinghouse Electric Corporation, Tampa Division, performed the half-bead weld repair of the cavity in vessel V-8, shown in Fig. 2, and in an identical cavity in a 600-mm-long prolongation of the test cylinder. [4] The prototypical weld in the prolongation provided material for determination of residual stresses and material properties.

The weld cavity was located across one edge of the fabrication weld so as to provide a choice among five different flaw sites near the repair: in base metal, in the base metal heat-affected zone (HAZ), in repair weld metal, in the fabrication weld HAZ, and in the fabrication weld. The axial sides of the cavity in the vessel were machined along radial planes so that their locations could subsequently be determined precisely.

Residual stresses were evaluated by two means, by measurement of strain changes on exposed surfaces of the vessel and prolongation and by the hole-drilling technique. [5] The vessel and prolongation were instrumented with weldable strain gages prior to repair welding and the changes in strain induced by welding were recorded for twenty locations on the prolongation near the repair and for twenty-five locations on the vessel. Subsequently the prolongation was cut into two rings so as to expose the central cross section of the repair weldment. Strain changes induced by this cut were measured and used as a basis for adjusting the residual stresses measured on the cut surface. Principal stresses were measured at 46 points on this surface by hole drilling. The same technique was used to measure outside-surface residual stresses at 24 points near the repair on the vessel. Additional surface measurements were made to evaluate the residual stresses induced during vessel fabrication.

The principal results of the residual stress investigation are summarized in Figs. 3, 4, and 5. These data show that residual stresses are low within the repair weld itself and rise to values near yield in nearby material at the outside surface.

The half of the prolongation not used for residual stress measurements was sectioned for the study of material properties. Hardness measurements were made across the section of the repair shown in Fig. 6. Tensile properties of the repair weld metal were determined from specimens taken from half-bead weld metal test plates made by Westinghouse with the specified E-8018-C3 welding electrodes. Fracture toughness of the various regions of the repair was evaluated by slow bend tests of precracked Charpy specimens and static

tests of 1T and 2T compact specimens taken from the prototypical weldment. Additional fracture specimens were obtained from the fabrication weld in another prolongation (V-9) fabricated with vessel V-8 and its prolongation.

Hardness measurements made along the three traverses across the HAZ's shown in Fig. 6 indicate that both base metal HAZ's are similar in hardness and are harder than any other region. The results along traverse A are presented in Fig. 7. These data imply that the repair weld-base metal HAZ has substantially higher yield and ultimate strengths than the plate or weld materials.

The tensile properties of the repair weld metal are compared in Table 1 with those of plate material from another prolongation (V-7) in this series.

The relative fracture toughnesses of the various zones of the repair weldment were evaluated by numerous slow-bend tests of precracked Charpy specimens. The values low in the transition range were of greatest interest in

Table 1. Tensile Properties

Material	Temperature (°C)	Strength (MPa)		Total elongation (%)	Reduction in area (%)
		Lower yield	Ultimate		
Weld	22.2	479	574	21	77
Weld	21.1	485	576	24	63
Weld	21.1	488	563		
Plate, CA ^a	25	454	596	22.6	73.4
Plate, AC ^a	25	455	607	18.3	69.4

^aSpecimens from 107 mm depth.

planning the V-8 test because low values were needed for a successful test. In specimens used to measure HAZ toughness the sharpened precracks were carefully placed within the HAZ. The lowest toughness values were found in the fabrication weld, while the repair weld exhibited the next lowest values and the HAZ's were at least as tough as the base material. These conclusions were also supported by the earlier HSST vessel test, V-7B. [2] Further evaluations of toughness were concentrated on the submerged-arc fabrication weld, particularly in the region close to the repair weld. (See Fig. 1.)

Pretest estimates of fracture toughness depended primarily upon data from 1T and 2T compact specimens taken from prolongations of vessels V-8 and V-9. Although these two pieces were fabricated with vessel V-8, the possibility of variability was considered, since high variability would suggest a greater uncertainty in attributing the measured toughnesses to the vessel itself. Results of the toughness study are presented in Fig. 8. The work of Canonico, Crouse, and Stelzman had shown a correlation between precracked Charpy data and the microstructure of the weld. [6,7] Hence, it was considered possible that the behavior of the larger fracture toughness specimens was controlled by the lower toughness structures within the weld. If that were the case, a sharp crack in the submerged-arc weld in the vessel (in the location shown in Fig. 1) would also tend to be controlled by these structures. Consequently, the lowest value of toughness ($\sim 100 \text{ MN}\cdot\text{m}^{-3/2}$) shown in Fig. 8 in the -25°C to -20°C range was chosen as an appropriate lower bound value of K_{Ic} for pretest analysis.

Experience in flaw preparation and testing favored the selection of a flaw size and geometry that were similar to those used in the first series of HSST intermediate vessel tests. [8] Preliminary calculations confirmed

the suitability of this selection. Accordingly, a notch 206 mm long and 50.5 mm deep was cut into the fabrication weld and fatigue sharpened to a total depth of 62.5 mm (Fig. 1). The fatiguing was accomplished by sealing the notch opening and pressurizing the notch cyclically. Acoustic emission detectors were used to sense crack activity and ultrasonic equipment measured the fatigue crack growth. The crack growth rate was significantly elevated by the residual stress field.

FRACTURE ANALYSIS METHODS

Previous intermediate vessel tests had demonstrated that analyses by means of linear elastic fracture mechanics (LEFM) accurately predict crack initiation pressure, provided initiation precedes the onset of gross yielding in the test section. In order to gain more assurance that the comparisons of LEFM and test results would not be confused by competing phenomena, it was decided that the test pressures should be limited to a range in which yielding would not occur in an unflawed cylinder. The upper limit on the test pressure was about 160 MPa, or $2.4 \times$ the design pressure.

Exploratory LEFM calculations of K_I for the combined loading from pressure and residual stress were based upon the work of Smith and Alavi [9] on part-circular surface flaws. Computations were made by means of Merkle's closed form solution for K_I for a linear radial stress distribution. [10] Finite-element calculations using the ADINA program with a 3-dimensional mesh were also made. [11] The crack geometry assumed for these calculations is given in Fig. 9 and the residual stress distribution in Fig. 10.

The residual stresses present in the uncut cylinder were treated in the calculation of K_I as though they resulted from a remotely applied load, which

was believed to be a reasonable assumption for a crack that did not extend far with respect to the size of the residual stress field. The pretest distribution shown in Fig. 10 fits the measured values at the circumferential centerline of the flaw and was assumed to be constant axially.

The results of the pretest calculations shown in Figs. 11 and 12 gave an indication of the margins for uncertainty that could exist in a comparison of theory and experiment. The "measured σ_r " line in Fig. 11 represented our best pretest prediction of K_I for the initial crack, with residual stresses taken into account; while the " $\sigma_r = 0$ " line was considered a reliable estimate of K_I in the absence of residual stresses. Hence, if the effect of residual stresses were grossly overestimated, but K_{Ic} was correctly assessed, the failure should occur at point A, for which the pressure is below the initial yield pressure. However, an underestimation of K_{Ic} could result in yielding before failure (point B) and an inconclusive test result. This situation demanded care in measuring K_{Ic} and in assuring that the vessel was cooled to -18°C or below.

The closed form solution for K_I is compared with the finite element results in Fig. 12 for the same crack depth and the same residual stress distribution and load.

VESSEL TEST

The test vessel was instrumented with strain gages, crack-opening displacement gages, pressure transducers, crack propagation gages, thermocouples, and acoustic emission detectors. The vessel was cooled to about -20°C before the start of pressurization; the temperature of the test section was maintained within $\pm 3\text{K}$ of -23°C during the test. The pressurizing medium was a mixture of ethylene glycol and water.

The pressurization proceeded as shown in Fig. 13. The crack popped in and arrested without causing leakage at 26.3 MPa. Continued pressurization resulted in a second pop-in and fluid leakage at 65.3 MPa.

POST-TEST EVALUATION

The flaw zone of vessel V-8 was sectioned extensively so that the fracture geometry and mode of fracture could be studied. The crack extension appears to be cleavage and is highly irregular and curved, as illustrated in Fig. 14. The depth of the crack after the first pop-in was estimated from the change in the COD compliance to be about 110 mm. The length of the crack at this stage is uncertain, but it is conjectured that most of the extension along the outside surface took place during this first extension. The depth of the first pop-in has been tentatively confirmed by scanning electron microscopic examination, and further studies of the fracture surfaces are being made to delineate the entire crack front at the time of arrest.

Stress intensity factors for the first pop-in have been calculated by the closed-form solution of Smith and Alavi used earlier and by a method of Shah and Kobayashi [12] for a buried elliptical crack. In the latter method, the axial variation of the residual stress field is taken into account. The assumed radial variation is given in Fig. 10 by the "post-test" line, which fits the measured points better than the pretest line for deep cracks. Post-test calculations and test results are compared in Fig. 15. The first and second crack extensions (points A and C) were observed at 26.3 MPa and 65.3 MPa, respectively, while the corresponding calculated values were 29 MPa and 63 MPa, based upon $K_{Ic} = 99 \text{ MN}\cdot\text{m}^{-3/2}$. The arrest toughness deduced from the

depth of the first pop-in (see point B) is $66 \text{ MN}\cdot\text{m}^{-3/2}$. The complex geometry of the final crack and the lack of data on residual stresses on that surface makes the analysis of the final crack impractical. Nevertheless, the value of K_{I} at the second initiation (point C) calculated for a straight crack agrees well with the measured fracture toughness.

CONCLUSIONS

The investigations of the HSST program of Section XI half-bead weld repairs on thick sections have led to several conclusions that may deserve consideration by persons contemplating weld repairs on pressure vessels.

(1) The mechanical and fracture properties of the materials in the repair zone are generally adequate.

(2) High tensile residual stresses are developed in the repair zone, the highest values occurring outside the weld deposit.

(3) The combined effects of residual stress and pressure stress were accurately predicted by linear elastic fracture mechanics for a case in which fracture toughness was low.

(4) Arrest of a cleavage mode fracture was demonstrated in the V-8 test, in which K_{I} was decreasing with increasing crack size.

ACKNOWLEDGMENTS

The authors wish to thank the Nuclear Regulatory Commission for their support of this research and the Electric Power Research Institute for their cooperation and financial support in the first vessel repair. We also wish to recognize the advice of the Task Group on Weld Repairs of the Pressure

Vessel Research Committee and the contributions of colleagues in the test program: D. A. Canonico, P. H. Hutton, D. J. Naus, J. E. Smith, G. C. Smith, and W. J. Stelzman.

REFERENCES

1. Bryan, R. H., et al., *Test of 6-in.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7A Under Sustained Loading*, ORNL/NUREG-9, Oak Ridge National Laboratory, Oak Ridge, TN, February 1978.
2. Bryan, R. H., et al., *Test of 6-in.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7B*, ORNL/NUREG-38, Oak Ridge National Laboratory, Oak Ridge, TN, October 1978.
3. *ASME Boiler and Pressure Vessel Code*, Section XI, "In-Service Inspection," Subsubarticle IWB-4420 (Repair Procedure No. 4).
4. Wismer, S. W. and Holz, P. P., *Half-Bead (Temper) Repair Welding for Heavy-Section Steel Technology Program Vessels*, ORNL/NUREG/TM-177, Oak Ridge National Laboratory, Oak Ridge, TN, June 1978.
5. Smith, G. C. and Holz, P. P., *Repair Weld Induced Residual Stresses in Thick-Walled Steel Pressure Vessels*, ORNL/NUREG/TM-153, Oak Ridge National Laboratory, Oak Ridge, TN, June 1978.
6. Stelzman, W. J. and Canonico, D. A., "Characterization of the Repair Weld in Vessel V-8," *HSSST Program Quart. Prog. Rep. July-September 1977*, ORNL/NUREG/TM-166, Oak Ridge National Laboratory, Oak Ridge, TN, April 1978, pp. 102-108.
7. Stelzman, W. J., Canonico, D. A., and Crouse, R. S., "Characterization of the Repair Weld in Vessel V-8," *HSSST Program Quart. Prog. Rep. October-December 1977*, ORNL/NUREG/TM-194, Oak Ridge National Laboratory, Oak Ridge, TN, May 1978, pp. 52-61.
8. Derby, R. W., et al., *Test of 6-inch-Thick Pressure Vessels. Series 1: Intermediate Test Vessels V-1 and V-2*, ORNL-4895, Oak Ridge National Laboratory, Oak Ridge, TN, February 1974.
9. Smith, F. W. and Alavi, M. J., "Stress-Intensity Factors for a Part-Circular Surface Flaw," *Proceedings of the First International Conference on Pressure Vessel Technology, Part II*, Delft, The Netherlands, ASME, 1969.
10. Merkle, J. G., *A Review of Some of the Existing Stress Intensity Factor Solutions for Part-Through Surface Cracks*, ORNL-TM-3983, Oak Ridge National Laboratory, Oak Ridge, TN, January 1973.
11. Bathe, Klaus-Jürgen, *ADINA - A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis*, Report 82448-1, Acoustics and Vibration Laboratory, Mechanical Engineering Dept., MIT, Cambridge, MA 02139.
12. Shah, R. C. and Kobayashi, A. S., "Stress Intensity Factor for an Elliptical Crack Under Arbitrary Normal Loading," *Eng. Fract. Mech.*, 3, 71-96, 1971.

FIGURE CAPTIONS

Fig. 1. Repair weld and flaw geometry for intermediate test vessel V-8.

Fig. 2. Repair weld cavity for V-8 and prolongation.

Fig. 3. Circumferential residual stresses of repair weld of vessel V-8 (in MPa). Measurements were made at midsection of the prototypical repair weldment. Values shown have been adjusted to account for relaxation from sectioning.

Fig. 4. Axial residual stresses on the surfaces of the V-8 and prototypical repair weldments (in MPa).

Fig. 5. Circumferential residual stresses on the surfaces of the V-8 and prototypical repair weldments (in MPa).

Fig. 6. Etched transverse section of V-8 prototypical half-bead repair weld. Locations of hardness traverses across the three types of heat-affected zones are labeled A, B, and C.

Fig. 7. Hardness traverse of the heat-affected zone between the SA533 base metal and the V-8 prototypical weld (traverse A in Fig. 6). Indentations are at 0.254-mm intervals.

Fig. 8. Variation of static fracture toughness of submerged-arc fabrication weld metal in prolongations of vessels V-8 and V-9. Precracked Charpy-V and 1T and 2T compact specimens were tested.

Fig. 9. Part-circular crack geometry assumed for the pretest calculations of K_I for V-8.

Fig. 10. Circumferential residual stress distributions assumed for calculations of K_I for V-8. Stresses were assumed not to vary axially except for the post-test calculations by the Shah and Kobayashi method.

Fig. 11. Variation of K_I with internal pressure in V-8 for no residual stress and for the pretest distribution shown in Fig. 10. The values plotted are those calculated by the finite-element code for the point of the flaw at which $\theta/\theta_{\max} = 0.5$.

Fig. 12. Comparison of the pretest calculations of K_I as a function of crack-tip location. The calculations were for part-circular geometries. Refer to Fig. 9 for definition of geometrical parameters.

Fig. 13. Pressurization history of the V-8 test.

Fig. 14. Configuration of the extended crack in vessel V-8.

Fig. 15. Comparison of calculated values of internal pressure with measured values for the two crack initiations in V-8. The implied value of crack-arrest toughness is also shown.

DIMENSIONS IN MILLIMETERS

Fig. 2

Fig. 3

OFNL-DWG 78-3994

SHELL END OF PROLONGATION
BOLTED HEAD END OF VESSEL

Fig. 4

Fig. 5

PHOTO Y-150199

Fig. 6

PHOTO X-150182

Fig. 7

Fig. 8

DIMENSIONS IN MM		
	ANALYSIS TYPE	
	SMITH & ALAYI	FINITE ELEMENT
a	63.5	63.5
b	102.9	110.0
R	115.1	127.0
θ_{max}	63.4°	60.0°

Fig. 9

FIG. 10

Fig. 11

Fig. 13

Fig. 10