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C (T) and large diameter pipe fracture evaluations of a fusion line crack in a bimetallic weld

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ABSTRACT: Bimetallic welds exist in numerous locations in PWR and BWR plants. Prior to this effort, little data existed on the fracture properties along the ferritic steel base metal to the austenitic weld fusion line. To address this, several cold-leg pipe bimetallic welds were obtained. The pipes were nominal 940-mm (37-inch) diameter by 76-mm (3-inch) thick pipe obtained from a cancelled Combustion Engineering plant. Data on the tensile properties of the various parts of the weld joint, Charpy data along the fusion line and C(T) tests to determine the J-R curves were obtained from one of the welds. Another weld was used in a full-scale pipe experiment with a circumferential through-wall crack along the carbon steel to Inconel weld fusion line. The pipe test results are compared with predictions using a number of fracture prediction analysis methods.

INTRODUCTION

In both BWRs and PWRs there are many locations where carbon steel pipes or components are joined to austenitic pipes or components with a bimetallic weld. The objective of the research described in this paper was to assess the accuracy of current pipe fracture analyses for the case of a crack along a carbon steel to austenitic weld fusion line. This work was conducted at Battelle-Columbus as part of the USNRC's Short Cracks in Piping and Piping Welds Research Program⁽¹⁾.

The bimetallic welds evaluated in this program were obtained as part of the Degraded Piping Program⁽²⁾ from a cancelled Combustion Engineering nuclear power plant. The welds joined sections of the carbon steel cold-leg piping system to stainless steel safe ends that were to be welded to stainless steel pump housings. The carbon steel pipe material was A516 Grade 70. The safe ends were fabricated from SA182 F316 stainless steel (forged TP316 stainless steel). The welds were fabricated by first buttering the beveled end of the carbon steel pipe with an ENiCrFe-3 (Inconel 182) electrode. The welds joining the buttered pipes and the stainless steel safe ends were then completed using a shielded-metal-arc weld (SMAW) process, using Inconel 182 weld rod.

MATERIAL PROPERTY DATA

Material property data and data from a large diameter pipe fracture experiment were developed. The material property data developed included longitudinal tensile data from specimens machined from the various parts of the weldment as well as data from Charpy and compact (tension), C(T), specimens with cracks located along the carbon steel to Inconel weld fusion line to determine the fracture toughness of the fusion line.

Table 1 presents the tensile properties of the three predominant materials that make up this weldment, i.e., the carbon steel pipe, the stainless steel safe end, and the Inconel shielded-metal-arc weld (SMAW). As can be seen in Table 1 the Inconel 182 SMAW is considerably stronger than either the F316 stainless steel safe end or the A516 Grade 70 carbon steel pipe materials. Table 2 shows a summary of the J values at crack initiation (J_i) for three of the materials that make up this bimetallic weld, i.e., the carbon steel pipe, the stainless steel safe end, and the fusion line of the carbon steel pipe and the Inconel 182 buttering passes.

Table 1. Comparison of quasi-static tensile yield and ultimate tensile strengths at 288 C (550 F) of the three materials that make up the bimetallic weld evaluated in the Short Cracks in Piping and Piping Welds program⁽¹⁾

Material	Yield Strength, MPa (ksi)	Ultimate Tensile Strength, MPa (ksi)
Carbon steel pipe ^(a)	210 (30.5)	510 (73.9)
Stainless steel safe end	157 (22.8)	415 (60.2)
Inconel SMAW	372 (54.0)	599 (86.9)

(a) For specimen machined near the midwall of the pipe.

Table 2. Comparison of J-values at crack initiation (J_i) at 288 C (550 F) for three of the materials that make up the bimetallic weld evaluated in the Short Cracks in Piping and Piping Welds program⁽¹⁾

Material ^(a)	Planform Size	Notch Geometry ^(b)	Percent Side- Grooved	J_i , kJ/m ² (in-lb/in ²)
Carbon steel pipe	1T	FC	20	185 (1,055)
Stainless steel safe end	1T	FC	0	2,233 (12,750)
Carbon steel/ Inconel 182 fusion line	2T	FC	0	347 (1,983)

(a) No fracture toughness properties were evaluated for the Inconel weld region of this bimetallic weld.

(b) FC = fatigue precrack.

Figure 1 shows the full J-R curves for the three materials. As can be seen in Table 2 and Figure 1, the toughness of the carbon steel pipe is less than that for the fusion-line region. This, along with the fact that the strength of the carbon steel pipe is significantly less than that of the Inconel weld, explains why the cracks in both the C(T) specimens and the pipe fracture tests tended to grow in the carbon steel pipe material rather than in the weld.

RESULTS FROM THE PIPE EXPERIMENT

The large diameter pipe experiment evaluated a circumferential through-wall crack along the bimetallic weld fusion line. The loading conditions were quasi-static, four-point bending. The test

temperature was 288 C (550 F). The maximum moment for this experiment was 6.95 MN-m (61,500 in-kips). The moment at crack initiation, as determined from the d-c electric potential data, was 6.77 MN-m (59,900 in-kips).

Comparisons of the crack-initiation moments and the maximum moments from this pipe experiment were made with predictions using a number of fracture prediction methods using the tensile properties of the carbon steel pipe, stainless steel safe end, and Inconel weld materials. Tables 3 and 4 present the results of those comparisons. Table 3 compares the experimental moment at crack initiation with the predicted initiation moments and Table 4 compares the maximum experimental moment with the predicted maximum moments. The major conclusion drawn as a result of this effort was that the fracture behavior of this bimetallic fusion line could be predicted with reasonable accuracy using the tensile properties of the carbon steel pipe material and the fusion-line fracture toughness properties in conjunction with conventional elastic-plastic fracture mechanics analyses. Conversely, using the stainless steel safe end tensile properties or the Inconel weld metal tensile properties resulted in situations where the analyses significantly underpredicted or overpredicted, respectively, the experimental moments. The fact that the carbon steel pipe tensile properties worked so well is believed to be due to: (1) the crack growing more in the carbon steel material, and most of the pipe test specimen being made from the carbon steel pipe material, and (2) the Inconel 182 weld metal being higher strength than the carbon steel base metal. Consequently, the carbon steel base metal strength properties were more appropriate to use than the weld metal properties in the simple pipe fracture analyses.

DISCUSSION

One point that should be emphasized is that the data presented in this paper, and the conclusions drawn from these data, are applicable only to this one class of bimetallic welds, i.e., a low strength carbon steel pipe welded to a stainless steel safe end using an Inconel weld procedure. The fracture behavior of other classes of bimetallic welds, made up of different material systems, may not be the same. For instance, for bimetallic welds associated with low alloy ferritic steel nozzle forgings, the combination of strength and toughness properties of the various materials may be such that the crack will grow in the weldment. In addition, if the bimetallic weld was made using a stainless steel weld procedure rather than an Inconel weld procedure, then the propensity for decarburization of the carbon steel heat-affected-zone (HAZ) would be increased. In such cases, the carbon in the ferritic material would want to migrate to the stainless steel weld metal due to the fact that the carbon is more soluble in the stainless steel than it is in the carbon steel. Lundin⁽³⁾ reported that decreasing the nickel content of the filler metal alters the carbon solubility, making the carbides more stable, changing the diffusivity, and in general increasing the carbon migration from the ferritic material. As a result, when stainless steel weld rod is used instead of Inconel for the weld buttered passes, there is a depletion of carbon in the ferritic HAZ, which results in a softening, i.e., a loss in strength, in this area. In such cases, the crack may grow into a softer, carbon-depleted, region near the heat-affected-zone of the carbon steel material. When that happens, the fracture moments may be less than would be predicted using the carbon steel pipe properties in conjunction with conventional elastic-plastic fracture mechanics analysis methods.

To see how the weld evaluated in this program compared with other bimetallic welds, a comparison was made with data from a program conducted at the Nuclear Research Institute (NRI) in Rez, Czech

Table 3. Comparison of the experimental moment at crack initiation for bimetallic weld pipe experiment with the fracture analyses predictions of the crack initiation moments (using fusion-line C(T) specimen J-R curve data)

Predictive Method	Predicted Crack Initiation Moment ^(a) , MN-m (Using Tensile Properties of)			Experimental ^(b) /Predicted Crack Initiation Moment (Using Tensile Properties of)		
	Carbon Steel Pipe	Stainless Steel Safe End	Inconel Weld	Carbon Steel Pipe	Stainless Steel Safe End	Inconel Weld
GE/EPRI	5.30	3.13	6.51	1.276	2.164	1.039
LBB.ENG2	5.89	3.42	7.41	1.149	1.978	0.914
LBB.NRC	6.70	4.34	7.39	1.011	1.558	0.916
LBB.GE	6.09	3.72	7.35	1.111	1.818	0.921
PARIS/TADA	6.52	5.85	6.44	1.039	1.157	1.051
R6	5.24	3.86	6.66	1.293	1.756	1.016

(a) Using fusion line C(T) specimen J_D-R curve

(b) Experimental moment at crack initiation = 6.77 MN-m

Table 4. Comparison of the maximum experimental moment for bimetallic weld pipe experiment with the fracture analyses predictions of the maximum moment

Predictive Method	Predicted Maximum Moment ^(a) , MN-m (Using Tensile Properties of)			Experimental ^(b) /Predicted Moment (Using Tensile Properties of)		
	Carbon Steel Pipe	Stainless Steel Safe End	Inconel Weld	Carbon Steel Pipe	Stainless Steel Safe End	Inconel Weld
GE/EPRI	6.37	3.81	7.96	1.092	1.826	0.874
LBB.ENG2	6.96	4.11	8.92	0.999	1.690	0.780
LBB.NRC	7.92	5.23	9.84	0.878	1.331	0.707
LBB.GE	7.25	4.50	8.75	0.960	1.546	0.794
PARIS/TADA	8.17	6.53	9.33	0.852	1.065	0.745
R6	5.73	4.15	7.89	1.213	1.677	0.881
NSC	8.41	6.58	11.18	0.827	1.056	0.622
DPZP	6.46	5.65	6.67	1.076	1.231	1.043
ASME	3.47 ^(c)	----	4.71 ^(d)	2.006 ^(c)	-----	1.475 ^(d)

(a) Using fusion line C(T) specimen J_D-R curve.

(b) Maximum experimental moment = 6.95 MN-m.

(c) Using Appendix H with safety factor of 1.0.

(d) Using Appendix C with safety factor of 1.0.

Republic*, where Charpy and J-resistance curves for several such welds were determined. The data for one of those welds are summarized in Figure 2. For comparison purposes, the data from the bimetallic weld evaluated in this program are also included in Figure 2. As can be seen in Figure 2, the fusion-line toughness of the weld evaluated in this program was a factor of three higher than the fusion-line toughness of the weld evaluated by NRI. A hardness minimum in the decarburized zone of the carbon steel adjacent to the fusion line was also observed in the NRI program. Furthermore, some of the compact specimens NRI tested from this region (some of which were tested at room temperature) failed by cleavage of the carbon steel about 1 mm (0.04 inch) away from the fusion line, i.e., beyond the decarburized layer.

Another factor influencing the fracture behavior of bimetallic weld joints is the difference in the coefficient of thermal expansion between the dissimilar materials. The nickel-based Inconel weld metals have a coefficient of thermal expansion between those of the ferritic and austenitic base metals. The coefficient of thermal expansion of the Inconel-type materials is 15.3 mm/mm/C (8.5 in/in/F) compared with 18.7 mm/mm/C (10.4 in/in/F) for stainless steel and 14.8 mm/mm/C (8.2 in/in/F) for carbon steel. As a result, at elevated temperature service, the major differential expansion stresses will be located primarily at the tougher stainless steel/weld metal interface if Inconel weld metal is used; whereas, the major differential expansion stresses will be located primarily at the less tough carbon steel/weld metal interface if stainless steel weld metal is used. Consequently, the use of the Inconel weld metal creates a situation where the higher stresses due to differential thermal expansion occur in a region that may be more tolerant of defects.

CONCLUSIONS

The major conclusion from this work was that the fracture behavior of the bimetallic weld evaluated in this effort could be predicted with reasonable accuracy using the tensile properties of the carbon steel pipe material and the fracture toughness properties of the weld fusion line in conjunction with conventional elastic-plastic fracture mechanics analyses. However, this conclusion may not be generally applicable to all classes of bimetal welds.

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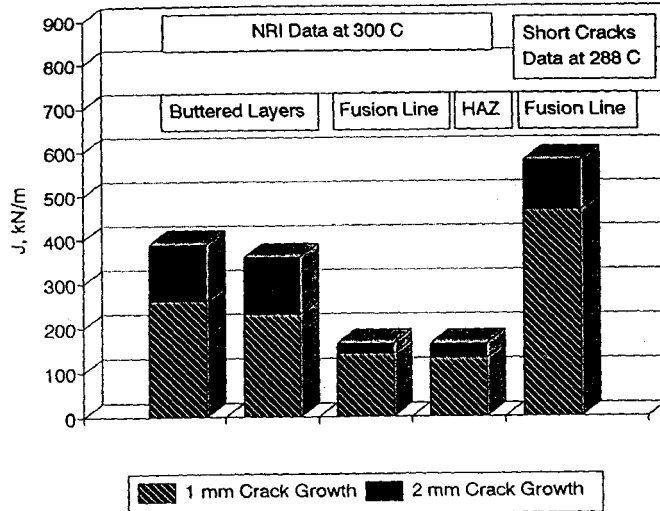


Figure 1. J-R curves for F316 stainless steel safe end, A516 Grade 70 carbon steel pipe, and fusion-line of the carbon steel and Inconel 182 buttering passes

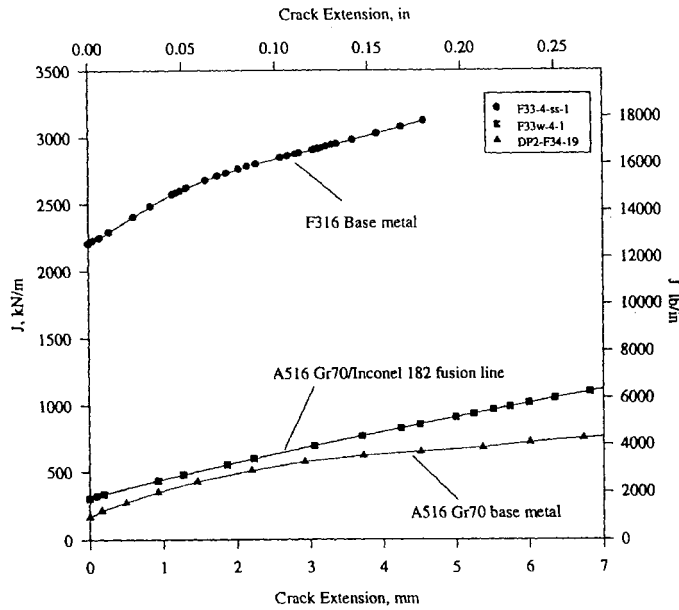


Figure 2. J-values at 1 mm (0.04 inch) and 2 mm (0.08 inch) of crack extension for bimetallic welds evaluated by NRI-Rez and from the Short Cracks in Piping and Piping Welds program⁽¹⁾