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Fracture toughness evaluation of stainless steel weld fusion lines

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ABSTRACT

In many past pipe fracture experiments, cracks were put in the centerline of a stainless steel pipe submerged arc weld, which was believed to be the lowest toughness region of the weld. However, frequently the cracks grew out of the centerline of the weld and followed the fusion line. In this study, Charpy V-notch and C(T) specimens were fabricated with the cracks following the fusion lines for two different weldments. One weld had a slant V groove so the fusion line was perpendicular to the plate surface. This allowed for standard Charpy and C(T) specimen testing. The other weld was an archival single-vee pipe weld, that required a slant notch in the C(T) specimens. The effects of Mode I and Mode II loading were taken into account in the slant notch specimens.

The results showed that the stainless steel weld fusion line J-R curve reached a steady-state value after a small amount of crack growth. So that even though the initiation toughness of the fusion line was higher than the weld metal, the weld metal J-R curve which increased with crack growth then becomes higher than the fusion line toughness. Consequently, the lower resistance fracture path quickly becomes the fusion line of the stainless steel welds.

OBJECTIVES

The objective of this effort was to evaluate the fracture toughness of the fusion line of austenitic steel submerged arc welds. The incentive was to explain why the cracks grew into the fusion line in many of the pipe tests which were conducted with cracks initially in the center of the weld. The concern is that the fusion line may have a much lower toughness than the submerged arc weld metal. Since the submerged arc weld metal toughness is considered the lowest toughness for pipe flaw evaluation in the ASME Section XI austenitic pipe flaw evaluation criteria, and would typically be used in LBB evaluations, the implication of this work is significant. Details of the work presented here are available in Reference 1.

EXPERIMENTAL WORK

To conduct this evaluation, Charpy V-notch and compact tension [C(T)] specimens were fabricated from two different welds. One weld was a standard single-Vee weld from a girth-welded pipe, and the other was a slant-Vee weld from a plate weld that had one of the fusion lines perpendicular to the plate surface. The standard single-Vee weld C(T) specimens had the notch machined along the fusion line, i.e., they had a slant notch. The slant-Vee weld C(T) specimens had standard (flat) notches machined along the fusion lines, that were perpendicular to the plate face. The C(T) specimens were tested at

288 C (550 F) at quasi-static monotonic loading rates. Charpy specimens were tested at room temperature and 288 C (550 F). Data for cracks in the center of the weld and in the base metal were available from previous work[2] for comparison with results in this program. Figures 1a and 1b show schematics of the specimens and crack orientation.

RESULTS

The quasi-static mechanical properties of the materials at 288 C (550 F) tested in this program are given in Table 1. The Charpy data for the weld fusion lines is given in Table 2. These data include the energy absorbed, lateral expansion, percent shear and a value of the fracture toughness parameter J obtained using the procedure recommended by ASME Section XI[3].

For the flat notched C(T) specimens, J was evaluated using ASTM E1152-87[4] for the slant notched specimens the crack is under mixed mode conditions, that is under Mode I and Mode III loading. Figure 2 illustrates the toughness at crack initiation for slant notched C(T) specimens. The value of J_{tot} is essentially the sum of the components J_i and J_{iii} for the mixed mode case. Another convenient measure is J_{nom} which is the value calculated assuming a flat crack whose width is equal to the specimen thickness. The analysis methods of Manoharan[5] were used to compute J from the experiments. Figure 3 shows the J-R curves for flat notch specimens using J_{nom}. The J-R curves for the slant notch specimens are shown in Figure 4. Results of all the C(T) specimens are summarized in Table 3. A comparison of J_{nom} resistance curves for base metal, weld, and fusion line is shown in Figure 5.

MAJOR FINDINGS

The major findings from this work are as follows:

(1) The value of toughness determined at the fusion line using a sharp crack specimen is highly sensitive to the crack tip location relative to the fusion line. This result was expected.

(2) The J_{1mm} values calculated from the Charpy energy data using the ASME Section XI Appendix H correlation were less than the C(T) specimen J_{Ic} values. Hence, the ASME Charpy energy correlation can be used, but it may be very conservative, e.g., by a factor of 9 in one case.

(3) From the data developed in this research, the initiation toughness of the stainless steel base metal is much higher than determined from either the SAW or the fusion line. The fusion-line initiation toughness J_{Ic} was greater than that at the SAW centerline.

(4) The crack growth resistance at the fusion line appeared to reach a steady-state value, while the SAW J-R curve had an increasing J_D-R curve. This result may explain why in the pipe experiments, the cracks eventually turn and grow along the fusion line. Also, this result implies that the weld metal J-R curve should be used up to the fusion-line steady-state J value for stainless steel welds. A large C(T) specimen test with the initial crack in the fusion line would help to confirm this conclusion.

(5) If the crack tip is slightly off the fusion line in the base metal, the initiation toughness may be high, but the crack can quickly grow into the lower toughness fusion line and produce a decreasing J-R curve. Such a decreasing toughness curve has not been observed when testing homogeneous specimens.

(6) The most important conclusion is that the fusion-line J-R curve results can have an impact on the ASME Section XI austenitic pipe flaw evaluation criteria and LBB analyses for wrought and probably cast stainless steels. In the past, the weld metal toughness has been the limiting toughness; whereas the fusion line and heat-affected-zone toughness have been given little attention.

DISCUSSION

Other factors that could also force the crack to follow the fusion line are: the center of the weld in most of the pipe experiments was thicker than the pipe due to the weld crown being left on. The crack may want to turn to the root of the weld where the pipe wall is thinner. Furthermore, there is a slight stress concentration at the toe of the weld crown. It has also been observed that on the inside of the pipe, the crack will go to either the toe of the weld or to the counterbore. The toe of the weld and counterbore are slight stress risers, which would help to guide the crack, like using side grooves in a laboratory specimen. However, in one pipe experiment the weld crown was removed, and the crack still followed the fusion line. Hence, the presence of a weld crown may help to make the crack turn to the fusion line, but it is not a sufficient condition to cause crack extension along the fusion line. Therefore, the fusion-line toughness aspect is relevant to all austenitic piping welds, whether the weld crown is ground off or not. Finally, as noted in prior work, the effect of residual stresses on ductile fracture in stainless steel pipe welds is not significant.

A final relative comparison involved comparing results from this program with those from experiments from the Degraded Piping Program. The implication from the comparison of the weld metal and fusion line crack-tip-opening angle data from single-edge notched tension, SEN(T), specimens was that the fusion-line toughness was a factor of 3 less than that of the weld even at small amounts of crack growth. The lower toughness of the fusion line at small amounts of crack growth was not observed in the work performed in this effort. A contributing factor may be the direction of crack growth in the SEN(T) versus C(T) specimens. In the C(T) tests performed in this effort, the crack is growing as a through-wall crack parallel to the weld; whereas, for the past SEN(T) specimens, the crack was growing as a surface crack. Conducting tests in the through-thickness or radial direction with SEN(T) or bend-bar specimens might help to clarify this discrepancy.

REFERENCES

(1) A. R. Rosenfield, P. R. Held, and G. M. Wilkowski, "Stainless Steel Submerged Arc Weld Fusion Line Toughness," NUREG/CR-6251, April 1995.

(2) Wilkowski, G. M., and others, "Analysis of Experiments on Stainless Steel Flux Welds," NUREG/CR-4878, April 1987.

(3) American Society of Mechanical Engineers, 1992 ASME Boiler and Pressure Vessel Code, Section XI, Appendix H, 1992 Edition, July 1, 1992. Published by American Society of Mechanical Engineers, New York, N.Y. 10017.

(4) ASTM standard E1152-87, "Test Procedure for Determining the J-R Curve".

(5) Manoharan, M., Hirth, J. P., and Rosenfield, A. R., "A Suggested Procedure for Combined Mode I - Mode III Fracture Toughness Testing," *J. Testing and Evaluation*, Vol. 18, pp 106-114, 1990.

Table 1. Quasi-static mechanical properties at 288 C (550 F)

	DP2-A8W4		DP2-F33-4	DP2-A53W	
Property	Pipe	Weld	Pipe	Plate	Weld
Hardness, Rockwell B*	86	92	68-70	86	92
Yield Strength, MPa (ksi)**	184 (26.6)	258 (37.4)	157 (22.8)	***	***
Ultimate Tensile Strength, MPa (ksi)	453 (65.8)	469 (68.0)	415 (60.2)	***	***
Elongation, pct.	45.9+	26.4++	43.6+	***	***
Reduction in area, pct.	***	***	76	***	***
J at initiation, kN/m (klb/in)	729 (4.16)	55 (0.315)	2,233 (12.8)	***	***
dJ/da, MPa (ksi)	538 (78.1)	135 (19.6)	187 (27.1)	***	***

* Room temperature data
** 0.2 percent offset
*** Not determined
\+ 25.4 mm (1 inch) gage section
\+\+ 20.3 mm (0.8 inch) gage section

Table 2. Charpy data for weld fusion lines

Temperature, C (F)	Energy, J (ft-lb)	Materal Expansion, mm (mils)	Percent Shear	J_{1mm}, kJ/m^2 ($in\text{-}lb/in^2$)
	Single-Vee weld DP2-A8W4			
23 (73)	60 (44)	0.44 (17.5)	100	77.0 (440)
23 (73)	49 (36)	0.42 (16.5)	100	63.0 (360)
23 (73)	76 (56)	0.58 (23)	100	98.1 (560)
Average	61.7 (45.3)	8.48 (19)	100	79.3 (453)
288 (550)	61 (45)	0.61 (24)	100	78.8 (450)
288 (550)	69 (51)	0.64 (25)	100	89.3 (510)
288 (550)	66 (49)	0.58 (23)	100	85.5 (490)
Average	65.3 (48.3)	0.61 (24)	100	84.6 (483)
	Slant-Vee weld DP2-A53W			
23 (73)	171 (126)	1.07 (42)	100	221 (1,260)
23 (73)	171 (126)	1.04 (41)	100	221 (1,260)
23 (73)	193 (142)	1.04 (41)	100	249 (1,420)
Average	178.3 (131.3)	1.05 (41.3)	100	230 (1,313)
288 (550)	349 (257)	1.05 (41.5)	100	450 (2,570)
288 (550)	251 (185)	0.85 (33.5)	100	324 (1,850)
288 (550)	347 (256)	1.09 (43)	100	448 (2,560)
Average	315 (232)	1.00 (39.3)	100	406 (2,320)

Table 3. Summary of compact specimen data(a)

Specimen No. DP2-	Notch Orientation	J at Initiation, kN/m (lb/in)	Initial dJ/da, MPa (ksi)
TP304 base metal crack location			
F33-4-SS-1	Flat	2,204 (12,600)	304 (44.1)
F33-4-SS-2	Flat	2,272 (13,000)	221 (32.0)
F33-4-SSS-1	Slant(b)	1,414 (8,080)	186 (27.0)
F33-4-SSS-2	Slant(b)	1,986 (11,400)	261 (37.9)
SAW single-Vee fusion-line crack location			
A8W4-FL-1	Slant	600 (3,420)	326 (47.2)
A8W4-FL-2	Slant	899 (5,132)(c)	400 (58.0)
A8W4-FL-3	Slant	803 (4,587)	76 (11.0)
A8W4-FL-5	Slant	762 (4,352)	354 (51.4)
SAW slant-Vee fusion-line crack location			
A53W1-FL-1	Flat	475 (2,717)	208 (30.1)
A53W1-FL-2	Flat	2,088 (11,923)(c)	-30 (-4.3)
A53W1-FL-3	Flat	1,324 (7,560)(c)	256 (37.1)
A53W1-FL-4	Flat	510 (2,912)	304 (44.1)
A53W1-FL-5	Flat	1,490 (8,508)(c)	134 (19.4)

(a) Slant-notch values are J_{nom}
(b) Slant notch specimens machined at an angle so crack plane breadth is the same as for flat notch specimens.
(c) Crack tip not on fusion line.

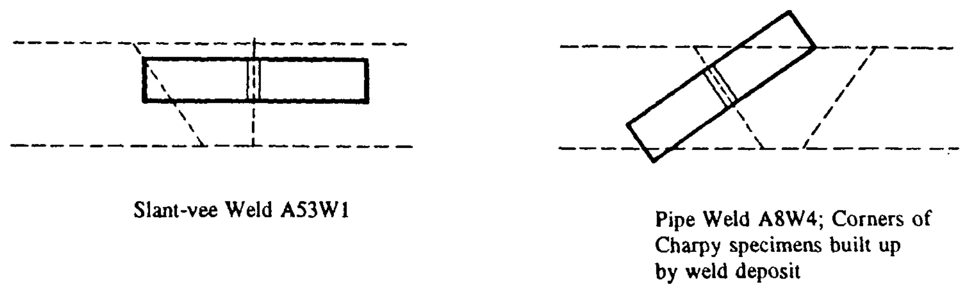

Figure 1a. Orientation of Charpy specimens

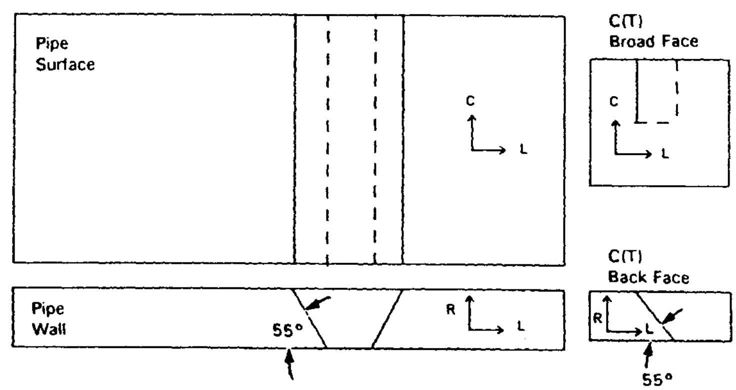

Figure 1b. Schematic diagram of compact specimen test geometry

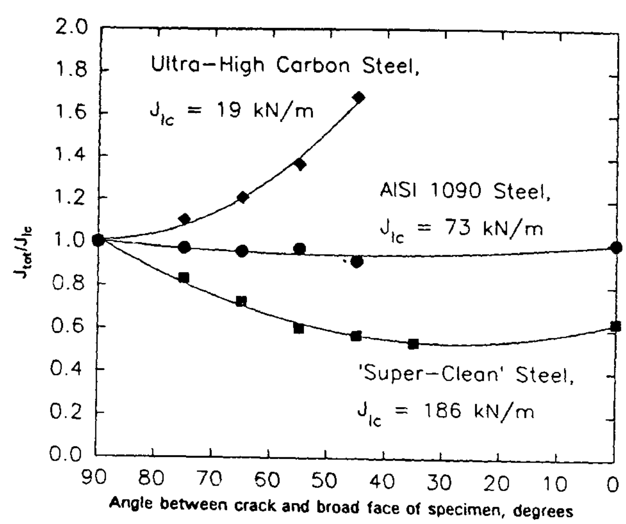

Figure 2. Initiation data for a variety of steels containing inclined precracks

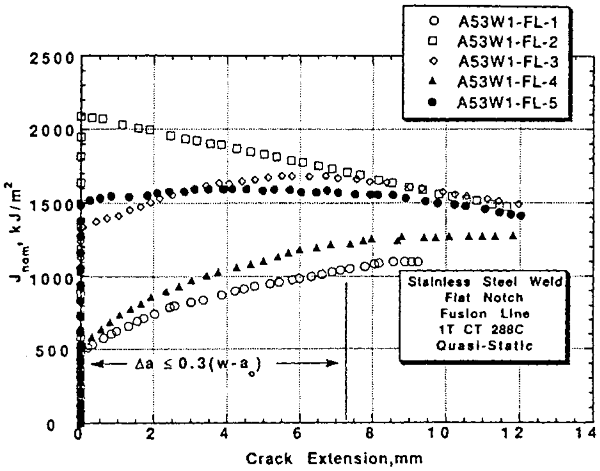

Figure 3. J-resistance curves for flat-notch, fusion-line specimens from DP2-A53W [limit on J-R curve data is $\Delta a \leq 0.3(W-a_0)$]

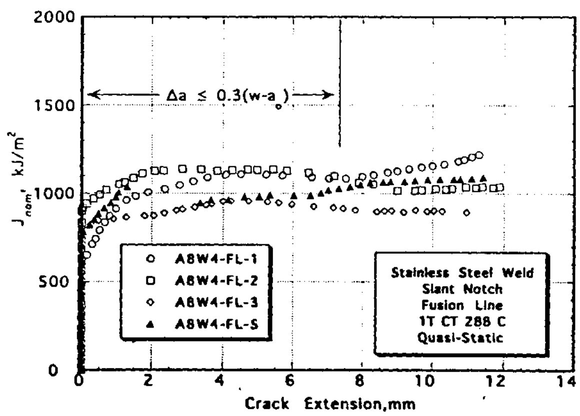

Figure 4. J-resistance curves of slant-notch, fusion-line specimens [limit on J-R curve data is $\Delta a \leq 0.3(W-a_0)$] (Note: The sudden load drop for Specimen A8W4-FL-5 corresponded to a significant crack jump as shown in the load-displacement data.)

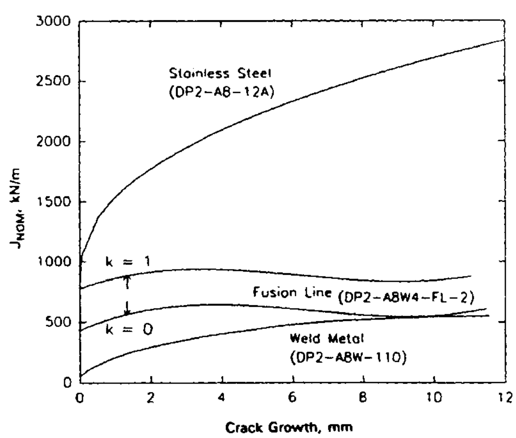

Figure 5. Comparison of J_{nom} resistance curves for base metal, weld, and fusion line