Stainless Steel Submerged Arc Weld Fusion Line Toughness

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ABSTRACT

This effort evaluated the fracture toughness of austenitic steel submerged-arc weld (SAW) fusion lines. The incentive was to explain why cracks grow into the fusion line in many pipe tests conducted with cracks initially centered in SAWs. The concern was that the fusion line may have a lower toughness than the SAW.

It was found that the fusion line, J_{Ic} was greater than the SAW toughness but much less than the base metal. Of greater importance may be that the crack growth resistance (J_D -R) of the fusion line appeared to reach a steady-state value, while the SAW had a continually increasing J_D -R curve. This explains why the cracks eventually turn to the fusion line in the pipe experiments. A method of incorporating these results would be to use the weld metal J-R curve up to the fusion-line steady-state J value. These results may be more important to LBB analyses than the ASME flaw evaluation procedures, since there is more crack growth with through-wall cracks in LBB analyses than for surface cracks in pipe flaw evaluations.

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EXECUTIVE SUMMARY

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.

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 line, which was 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 for comparison with results in this program.

The results showed that:

- (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 report, 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.

Executive Summary

- (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.

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 in 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.

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NOMENCLATURE

1. SYMBOLS

a	Crack length
a_o	Initial crack length
CVN	Charpy V-notch
J	Path-independent J integral
J_D	Deformation theory J-integral
J_{1mm}	J-integral value at 1 mm of crack growth
J_{Ic}	J integral at onset of crack growth for pure Mode-I loading
J_{IIIc}	J integral at onset of crack growth for pure Mode-III loading
J_M	Modified J-integral
J_i	Mode-I component of J integral under mixed-mode loading
J_{ic}	Value of J_i at onset of crack growth for mixed-mode loading
J_{iii}	Mode-III component of J integral under mixed-mode loading
J_{iiic}	Value of J_{iii} at onset of crack growth for mixed-mode loading
J_{nom}	For a slant-notch specimen, the value of J calculated using the measured load/displacement/crack-growth history and assuming a flat crack whose width is equal to the specimen thickness
J_{ss}	Steady-state or constant J value reached in a J-R curve
J_{tot}	Sum of Mode-I and Mode-III components of J integral
k	Parameter in mixed-mode failure criterion in Equation 2.2
U	Electric potential
U_o	Electric potential at crack initiation
W	Specimen width

Nomenclature

θ	Angle between specimen face and crack plane
σ_y	Yield strength

2. ACRONYMS AND INITIALISMS

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
BWR	Boiling Water Reactor
C(T)	Compact (tension) specimen
CTOA	Crack tip opening angle
DTRC	David Taylor Research Center
EPRI	Electric Power Research Institute, USA
GE	General Electric
HAZ	Heat-affected zone
IGSCC	Intergranular stress corrosion cracking
IPIRG-1	First International Piping Integrity Research Group
J-R	J-resistance (curve)
J _D -R	Deformation theory J-resistance (curve)
LBB	Leak before break
L-C	Orientation that indicates crack plane is normal to longitudinal axis (L) and crack growth direction is circumferential (C), corresponding to a circumferential through-wall crack in a pipe
L-R	Orientation that indicates crack plane is normal to longitudinal axis (L) and crack growth direction is radial (R), corresponding to a circumferential surface crack in a pipe
NDE	Non-destructive evaluation

Nomenclature

NRC	Nuclear Regulatory Commission
SAW	Submerged-arc weld
SMAW	Shielded-metal-arc weld
SEN(T)	Single-edge notched (tension) specimen

PREVIOUS REPORTS IN SERIES

Previous Reports from Short Cracks in Piping and Piping Welds Program

"Short Cracks in Piping and Piping Welds," First Semiannual Report, NUREG/CR-4599, Vol. 1, No. 1, March 1991.

"Short Cracks in Piping and Piping Welds," Second Semiannual Report, NUREG/CR-4599, Vol. 1, No. 2, April 1992.

"Short Cracks in Piping and Piping Welds," Third Semiannual Report, NUREG/CR-4599, Vol. 2, No. 1, September 1992.

"Short Cracks in Piping and Piping Welds," Fourth Semiannual Report, NUREG/CR-4599, Vol. 2, No. 2, February 1993.

"Short Cracks in Piping and Piping Welds," Fifth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 1, October 1993.

"Short Cracks in Piping and Piping Welds," Sixth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 2, March 1994.

"Effect of Dynamic Strain Aging on the Strength and Toughness of Nuclear Ferritic Piping at LWR Temperatures," NUREG/CR-6226, October 1994.

Previous Related Documents from NRC's Degraded Piping Program

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 1, October 1984.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 2, June 1985.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 3, March 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 4, July 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 5, December 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 6, April 1988.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 7, March 1989.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 8, March 1989.

"NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," Topical Report, NUREG/CR-4572, March 1986.

Previous Reports in Series

"Elastic-Plastic Finite Element Analysis of Crack Growth in Large Compact Tension and Circumferentially Through-Wall-Cracked Pipe Specimen--Results of the First Battelle/NRC Analysis Round Robin," Topical Report, NUREG/CR-4573 September 1986.

"An Experimental and Analytical Assessment of Circumferential Through-Wall Cracked Pipes Under Pure Bending," Topical Report, NUREG/CR-4574, June 1986.

"Predictions of J-R Curves With Large Crack Growth From Small Specimen Data," Topical Report, NUREG/CR-4575, August 1986.

"An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending," Topical Report, NUREG/CR-4687, September 1986.

"Analysis of Cracks in Stainless Steel TIG Welds," Topical Report, NUREG/CR4806, November 1986.

"Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipes," Topical Report, NUREG/CR-4853, January 1987.

"Assessment of Design Basis for Load-Carrying Capacity of Weld-Overlay Repair," Topical Report, NUREG/CR-4877, February 1987.

"Analysis of Experiments on Stainless Steel Flux Welds," Topical Report, NUREG/CR-4878, February 1987.

"Experimental and Analytical Assessment of Circumferentially Surface-Cracked Pipes Under Bending," Topical Report, NUREG/CR-4872, April 1987.

Previous Related Documents from NRC's International Piping Integrity Research Group (IPIRG) Program

"Evaluation and Refinement of Leak-Rate Estimation Models," NUREG/CR-5128 Revision 1, June 1994.

"Loading Rate Effects on Strength and Fracture Toughness of Pipe Steels Used in Task 1 of the IPIRG Program," Topical Report, NUREG/CR-6098, October 1993.

"Stability of Cracked Pipe Under Inertial Stresses - Subtask 1.1 Final Report," NUREG/CR-6233, August 1994.

Previous Reports from Other NRC Programs

"Validation of Analysis Methods for Assessing Flawed Piping Subjected to Dynamic Loading," NUREG/CR-6234, August 1994.

1.0 INTRODUCTION

1.1 Background and Incentives for the Project

The initial concern for intergranular stress corrosion cracks (IGSCC) in BWRs occurred in 1974, Refs. 1.1 and 1.2, and was for small pipe, [i.e., 102-mm (4-inch) diameter by 8.9-mm (0.35-inch) thick]. The work in References 1.1 and 1.2 showed that cracks occurred in the HAZ in stainless steel pipe typically at a distance of 2.5 to 6.35 mm (0.1 to 0.25 inch) from the weld fusion line, see Figure 1.1. Fracture toughness evaluations of sensitized TP304 stainless steel, Refs. 1.3 and 1.4, showed that sensitized stainless steel at these distances from the fusion line had a toughness equivalent to that of unsensitized wrought stainless steel, which has very high toughness.

Around 1982, cracks were found in larger diameter recirculation line BWR piping. In particular, the 711-mm (28-inch) diameter by 30.2-mm (1.19-inch) thick pipe in the Nine Mile Point plant main recirculation line showed cracks that occasionally grew from the base metal into the weld metal, see Figure 1.2 from Reference 1.5. However, more often the cracks grew along the fusion line of the weld, see Figure 1.3.

Figure 1.1 IGSCC in 102-mm (4-inch) diameter BWR recirculation bypass line (Loop B of the Quad Cities II reactor)

Figure 1.2 IGSCC in Nine Mile Point Plant; 711-mm (28-inch) diameter main recirculation line with a crack growing into the weld metal

Figure 1.3 IGSCC in Nine Mile Point Plant; 711-mm (28-inch) diameter main recirculation line with cracks growing along the fusion line

The occurrence of the cracks in the weld metal raised considerable concern about the fracture behavior of BWR pipes, particularly those fabricated with low toughness flux (SAW and SMAW) welds. In particular, the question arose as to whether IGSCC was occurring in an unusually low toughness region of the pipe, which could lead to premature rupture. DTRC in 1981 first showed that stainless steel flux welds can have significantly lower toughness than the base metal, see Figure 1.4 from Reference 1.6. The DTRC results from Reference 1.6 were subsequently verified by work in the NRC's Degraded Piping program, Figure 1.5 from Reference 1.7, and EPRI funded work at GE and Westinghouse, Refs. 1.8 and 1.9. The Westinghouse data were subsequently used in the ASME Section XI IWB-3640 austenitic pipe flaw evaluation procedures, where the lower toughness of flux weld metal was accounted for by an approximate elastic-plastic correction to the limit-load analysis. This correction factor, called a Z-factor, was a correction on the allowable stress.

During the course of the NRC's Degraded Piping Program, Ref. 1.7, an initial scoping study was conducted to evaluate the toughness of cracks in the HAZ and weld metal in the L-R orientation, which corresponds to a circumferential surface-crack growing through the thickness. In contrast, References 1.6, 1.8, and 1.9 involved C(T) specimens in the L-C orientation, which corresponds to growth of a circumferential through-wall crack in a pipe. The L-R orientation toughness study in Reference 1.7 involved single-edge notched tension, SEN(T), fracture tests. The results showed that the base metal had a high toughness, as is evident by the large crack-tip-opening angle (CTOA) of about 25 degrees in Figure 1.6, and the shielded metal arc weld (SMAW) had a lower toughness with a CTOA of about 12 degrees. For the HAZ specimens, if the crack stayed in the sensitized base metal, the CTOA was similar to that of the base metal, which confirmed the prior studies in References 1.3 and 1.4. However, in one specimen the crack grew along the fusion line with a significantly lower CTOA of about 4 degrees. The implication of this finding was that the fusion line toughness could possibly be much lower than that of the SMAW. Unfortunately, the SEN(T) specimen thickness was very large, about 76 mm (3 inch), and the crack grew into the fusion line only along one half of the specimen, which made a J-R curve analysis impossible. Since a J-R curve for the fusion line could not be calculated from this specimen, only CTOA observations could be reported.

Additional interesting results came from several pipe fracture experiments in other NRC-funded programs. These pipe experiments consistently showed that with the initial crack in the center of a low toughness SAW, the crack frequently grew out of the center of the weld and followed the fusion line. Several examples are cited below.

- Figure 1.7 shows a schematic of the crack growth paths from two Degraded Piping program experiments. Frequently, the crack followed the fusion line. This occurred in 406-mm (16-inch) and 152-mm (6-inch) diameter TP304 stainless steel pipe experiments at 288 C, Ref. 1.7.
- This same behavior occurred in Pipe Experiment 1.1.1.23 in the Short Cracks in Piping and Piping Welds program, Ref. 1.10. This test was conducted at 288 C (550 F) on a 711-mm (28-inch) diameter TP316 pipe from the Nine Mile Point plant. Figure 1.8 shows metallographic sections of the initial notch location and the crack growth paths.

(a) Base metal data

(b) Weld metal data

Figure 1.4 Stainless steel base metal and weld J-R curve data from DTRC, Ref. 1.6

Figure 1.5 Comparison of TP304 base metal and SAW J-R curves at 288 C (550 F), Ref. 1.7

Figure 1.6 Crack propagation in base metal, HAZ remote from fusion line, and weld metal in single-edge notch tension specimens at 288 C (550 F), Ref. 1.7

(a) Crack growth in HAZ as seen at one crack tip in Experiment 4141-1

(b) Crack growth in SAW extending out to internal counterbore as seen at one crack tip in Experiment 4141-1 and at both crack tips in Experiment 4141-3

Figure 1.7 Crack propagation behavior at 288 C (550 F) in 152-mm (6-inch) and 406-mm (16-inch) diameter TP304 pipe experiments with a circumferential through-wall crack initially in the center of a SAW, Ref. 1.7

(a) Initial crack tip location in center of weld

(b) Crack propagation paths

Figure 1.8 Crack propagation at 288 C (550 F) along fusion line of a TP316 SAW from a 711-mm (28-inch) diameter pipe test, Ref. 1.10 (Weld crown ground off prior to test)

- From the IPIRG-2 program currently on-going at Battelle, an experiment was conducted on a 406-mm (16-inch) diameter pipe with a surface crack initially in the center of the SAW. The crack followed the fusion line once the crack grew past the initial surface flaw location. Figure 1.9 shows the fracture surface from that experiment. The weld beads along the fusion line can easily be seen in this figure.

Therefore, incentives for conducting this program on fusion line toughness were:

- (a) IGSCC in thicker wall piping tended to grow more often along the fusion line than in the weld metal.
- (b) A low CTOA value was observed in the SEN(T) fusion line specimen.
- (c) Many of the pipe experiments resulted in cracks tending to follow the fusion line rather than staying in the low toughness SAW.

1.2 Report Outline

This report integrates the results from past programs and describes an experimental program involving laboratory tests, i.e., Charpy and C(T) specimens, to evaluate the toughness of the fusion line of typical TP304 stainless steel SAWs.

The experimental program is described in Section 2. Both flat-notch and slant-notch C(T) specimens were tested, the latter to simulate a circumferential crack growing along the fusion line of a girth weld in pipe experiments. Questions raised about the combined Mode I and Mode III loading imposed on the crack in the slant-notch specimens are addressed in Section 2, along with prior work on slant-notch C(T) testing.

Section 3 provides a summary and conclusions.

(a) Crack tip on Side A

(b) Crack tip on Side B

Figure 1.9 Crack propagation at 288 C (550 F) along fusion line of 406-mm (16-inch) diameter pipe with initial circumferential surface crack in center of a SAW

1.3 References

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- 1.4 Kanninen, M. F., and others, "Instability Predictions for Circumferentially Cracked Type 304 Stainless Steel Pipes Under Dynamic Loadings," Final Report on EPRI Project T118-2, by Battelle Columbus Laboratories, EPRI Report Number NP-2347, April 1982.
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- 1.6 Gudas, J. P. and Anderson, D. R., "J-R Characterization of Piping Materials and Welds," U.S. NRC 9th Water Reactor Safety Research Information Meeting, Washington, D. C., October 1981.
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- 1.8 Horn, R. M., and others, "Evaluation of the Toughness of Austenitic Stainless Steel Pipe Weldments," EPRI report NP-4668, June 1986.
- 1.9 Landes, J. D., and McCabe, D. E., "Toughness of Austenitic Stainless Steel Pipe Welds," EPRI NP-4768, October 1986.
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2.0 EXPERIMENTAL PROGRAM

The experimental program consisted of conducting Charpy and J-R curve tests with the cracks in the fusion line of stainless steel submerged arc welds. Since typical single-Vee welds would have the fusion line at an angle through the thickness, a special slant-Vee weld was made to allow fabrication of flat-notch C(T) specimens. This weld was made in TP304 stainless steel plate material.

Additionally, there was a standard single-Vee girth weld made in the past in a 406-mm (16-inch) diameter pipe using the same weld procedures. The pipe and plate were approximately the same thickness, i.e., 25.4 mm (1.0 inch). The standard pipe weld required the C(T) specimens to have a slant notch. A technical background section on past slant notch tests and analyses is given in Section 2.3.1. In addition, some base metal stainless steel flat and slant notch C(T) specimens were fabricated with the notch in the same plane.

2.1 Materials

The chemical compositions of the materials evaluated as part of this effort are provided in Table 2.1 and their mechanical properties are in Table 2.2. Note that the strength of both welds exceeded that of the base plates; that is, the welds were overmatched.

2.1.1 Preliminary Base Metal Experiments (Steel DP2-F33-4)

These C(T) tests were conducted using steel from a Type 316 stainless steel safe end, which had a diameter of approximately 914 mm (36 inches) and a wall thickness of 81 mm (3.2 inches). The objective of the preliminary slant-notch experiments was to ensure that the room temperature test procedures could be extended to 288 C (550 F) and to assess the J_i and J_{III} components in conducting tests where material anisotropy effects are not a factor.

2.1.2 Flat-Notch Fusion-Line Experiments (Weld DP2-A53W)

Two plates of Type 304 stainless steel, 25.4-mm (1-inch) thick, were joined by the submerged arc welding procedure given in NUREG/CR-4878, Ref. 2.1. The slant-Vee weldment cross-section profile is shown in Figure 2.1. Welding was done by the Uni-Facs Corporation of Columbus, Ohio.

The purpose of preparing such a profile is to have one of the fusion lines perpendicular to the plate surfaces to facilitate the machining of compact specimens and Charpy specimens having the notch located at the fusion line and through the thickness (denoted flat-notch in this report). We also considered a K-weld preparation. However, that procedure has the higher-heat-input root passes in the middle of the thickness. This fact may cause the fusion line to bulge out-of-plane there, which is undesirable (see Figure 2.2). The slant-Vee root passes are near one surface, and out-of-plane

Table 2.1 Chemical composition of test materials

Element	Percent by Weight				
	DP2-A8W4		DP2-F33-4	DP2-A53W	
	Pipe	Weld	Pipe	Plate	Weld
C	0.055	0.05	0.01	0.05	0.03
Mn	1.25	2.4	1.3	2.0	2.5
P	0.019	0.03	0.03	0.03	0.02
S	0.000	0.012	< 0.01	0.002	0.008
Si	0.70	0.63	0.63	0.40	0.58
Cu	0.12	0.21	0.32	0.17	0.061
Sn	0.007	0.01	0.01	0.01	0.01
Ni	7.7	9.8	12.2	8.6	9.2
Cr	17.0	20.0	16.1	19.0	20.3
Mo	0.017	0.18	2.1	0.42	0.15
Al	0.008	0.02	0.02	0.02	0.03
V	0.08	0.09	0.06	0.09	0.06
Nb	0.016	0.01	0.041	0.03	0.01
Zr	0.002	0.007	0.001	0.002	0.009
Ti	0.029	0.006	0.005	0.005	0.006
B	0.0021	0.0021	0.0002	0.0002	0.0002
Ca	*	0.0007	0.0013	0.0016	0.0007
Co	0.12	0.14	0.341	0.13	0.07
Fe	Balance	66.8	66.4	69.4	66.8

* Not determined

Table 2.2. Quasi-static mechanical properties at 288 C (550 F)

Property	DP2-A8W4		DP2-F33-4	DP2-A53W	
	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

+++ Reference 2.9

Figure 2.1 Slant-Vee weld in Plate DP2-A53

Table 2.3 Typical self-shielded flux-cored arc-welding procedures for stainless steels using stainless steel electrodes (from AWS Welding Handbook - Volume 2)

Joint Design	Weld Size, T		Root Opening, R		Total Passes	Electrode diameter		Welding power dcrp (ep)		Production rate		Electrode extension	
	mm	inch	mm	inch		mm	inch	A	V	m/h	ft/h	mm	inch
10	3/8	10	3/8	3	2.38	3/32	300	27.5	6	20	25	1
	32	1-1/4	10	3/8	8	2.38	3/32	300	27.5	2	5	25-32	1 to 1-1/4

bulging of the fusion line could be machined away. Note that the slant Vee weld preparation is a standard weld preparation (see Table 2.3, which came from the AWS Welding Handbook - Volume 2, Reference 2.2).

2.1.3 Slant-Notch Fusion-Line Experiments (Weld DP2-A8W4)

The pipe used for these experiments was seam welded, Schedule 100, ASTM A358, Type 304 stainless steel having a diameter of 406 mm (16 inches) and a wall thickness of 26.2 mm (1.032 inches). Specimens were taken from the submerged-arc girth weld, which had the profile given in Figure 2.3. Standard J-R curve data for the pipe and the center of the weld metal in that weldment had been determined previously in Reference 2.1.

These experiments combined features of the previous two series: slant-notch geometry plus precrack positioned along the fusion line.

2.2 Charpy Tests

Charpy specimens were tested to determine whether Charpy V-notch impact test data could be used to determine the fusion line toughness. The specimens were machined so that the notches were along the fusion lines according to the sketches in Figure 2.4. As noted in Table 2.4, both fusion lines showed complete ductile fracture at both room temperature and 288 C (550 F). However, the slant-Vee weld, DP2-A53W, had considerably higher notch toughness than did the single-Vee weld, DP2-A8W4.

2.5X

Figure 2.2 Example of K-weld preparation with out-of-plane bulging of the fusion line at the root passes

Figure 2.3 Single-Vee pipe Weld DP2-A8W4
(Slant notch put along left fusion line.)

Figure 2.4 Orientation of Charpy specimens

Table 2.4 Charpy data for weld fusion lines

Temperature, C (F)	Energy, J (ft-lb)	Lateral Expansion, mm (mils)	Percent Shear	J_{lim}^* , kJ/m ² (in-lb/in ²)
<u>Single-Vee weld DP2-A8W4</u>				
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)	<u>76 (56)</u>	<u>0.58 (23)</u>	<u>100</u>	<u>98.1 (560)</u>
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)	<u>66 (49)</u>	<u>0.58 (23)</u>	<u>100</u>	<u>85.5 (490)</u>
Average	65.3 (48.3)	0.61 (24)	100	84.6 (483)
<u>Slant-Vee weld DP2-A53W</u>				
23 (73)	171 (126)	1.07 (42)	100	221 (1,260)
23 (73)	171 (126)	1.04 (41)	100	221 (1,260)
<u>23 (73)</u>	<u>193 (142)</u>	<u>1.04 (41)</u>	<u>100</u>	<u>249 (1,420)</u>
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)
<u>288 (550)</u>	<u>347 (256)</u>	<u>1.09 (43)</u>	<u>100</u>	<u>448 (2,560)</u>
Average	315 (232)	1.00 (39.3)	100	406 (2,320)

* Estimated from Equation (2.1).

The ASME Section XI Appendix H correlation between Charpy energy and J at 1 mm (0.039 inch) of crack extension was used to calculate the $J_{1\text{mm}}$ values given in Table 2.4. Strictly speaking this correlation was validated only for ferritic steels (including HAZ), but in past evaluations at Battelle it was found to work well for austenitic SAWs also. This equation is

$$J_{1\text{mm}} = a(\text{CVN}) \quad (2.1)$$

where

$a = 10$ when $J_{1\text{mm}}$ is in units of in-lb/in², and CVN is Charpy energy in units of ft-lbs.

and

$a = 1287$ when $J_{1\text{mm}}$ is in units of N/m, and CVN is in units of Joules.

2.3 Fracture Toughness Tests

As noted in the introduction, two different welds were used in the experiments. One weld had the fusion line perpendicular to a plate so that the notch was also perpendicular to the plate; the other weld was a standard single-Vee weld, which required a slant notch in the C(T) test specimens. Because the slant notch specimen is non-standard, some additional technical background on this specimen geometry is given.

2.3.1 Background on Slant-Notch Specimen Testing

The experiments described in this section were initiated to evaluate a method for testing archival standard single-Vee weldments for plant-specific applications. As discussed in Section 1, failure of piping has been observed along fusion lines in welded pipe. In order to measure fracture toughness associated with this type of crack growth, we fabricated compact specimens from weldments and aligned the notch and precrack with the weld fusion line. Two designs were used because two fusion-line orientations were evaluated. No design modifications were needed for testing a fusion line normal to the plate surface (i.e., the broad face of the specimen). However, when the fusion line was inclined at an angle of 55 degrees to the pipe surface, modifications of the standard compact specimen design were required. The guideline was that the stress system resolved on the fusion line must reflect the stress system associated with pipe rupture. Figure 2.5 shows the geometric relations between pipe and compact specimen that were used to satisfy this requirement. The figure represents the case where the loading on the specimen simulates axial bending of the pipe. Because of the inclined nature of the crack plane, its tip is subjected to both Mode-I (opening) and Mode-III (transverse shear) loadings.

Figure 2.5 Schematic diagram of compact specimen test geometry

A variety of steels have been tested in other programs at Battelle using the slant-notch geometry, and several behaviors have been reported in References 2.3 and 2.4. The initial research was conducted using a very tough steel, designated ASTM-A710. At initiation, this material exhibited total values of J ($J_{\text{tot}} = J_i + J_{\text{iii}}$)^(a) that were fairly insensitive to crack orientation; however, J_{tot} became sensitive to crack angle after 3 mm of crack growth, passing through a minimum between pure Mode-I and pure Mode-III loading. This result suggested a complex relation between the J-R curve and crack-plane orientation. In Reference 2.5, Schroth, and others, argued that lower J values for mixed-mode failure were consistent with the observation that large structures of high toughness steels fail along inclined planes. Subsequently, in Reference 2.3, Manoharan, and others, suggested that the minimum occurs when the crack opening (Mode-I) displacement falls to a value about equal to the surface roughness, and that the increase in toughness as the crack plane becomes more closely parallel with the specimen surface is due to frictional rubbing associated with Mode-III displacements.

Later research revealed that the minimum in the toughness-versus-orientation curve does not always occur in mixed-mode fracture. Figure 2.6 illustrates initiation data and shows examples of the differing behaviors that have been observed in References 2.6, 2.7, and 2.8. The data in this figure suggest that there are situations where measuring J_{ic} is sufficient to obtain the minimum toughness. According to the analysis of the extensive data base by Kamat and Hirth in Reference 2.9, J_{ic} is the

(a) We have used the terminology J_i and J_{iii} to characterize J components in mixed-mode loading and to emphasize that the data were generated using a non-standard specimen.

Figure 2.6 Initiation data for a variety of steels containing inclined precracks^(a)

minimum toughness at two extremes: brittle materials ($J_{ic}/\sigma_y < 0.1$ mm) and very tough materials ($J_{ic}/\sigma_y > 0.7$ mm). For materials of intermediate toughness, the minimum lies somewhere in J_I - J_{III} space. However, it should be pointed out that Kamat and Hirth did not include stainless steel in their correlation.

A simpler representation of the mixed-mode fracture criterion is illustrated by Figure 2.7. Here it is seen that the J_{ic} versus J_{IIIc} relation is linear except for J_{ic} levels below about 30 percent of J_{Ic} . For these low levels, the J_{IIIc} levels are higher than might be anticipated by extrapolation of the linear portion of the curve, suggesting that rubbing induces an apparent added component to toughness. Figure 2.7 also suggests that a linear relation may be used to characterize other materials where the data are more limited, provided caution is used regarding accounting for rubbing. This linear relation can be expressed as the failure criterion:

$$J_{ic} + kJ_{IIIc} = J_{Ic} \quad (2.2)$$

The failure criterion is $J_{tot} = J_{Ic}$ for the special case where $k = 1$.

As part of the data reduction procedure, it is also convenient to calculate J_{nom} , which is defined as the value of J calculated using the measured load/displacement/crack-growth history and assuming a flat

(a) The zero-degree points on this graph were obtained using the pure shear specimen described in Reference 2.8.

Figure 2.7 Relation between opening-mode and shear-mode toughness

Figure 2.8 Effect of angle of crack plane on nominal fracture toughness

crack whose width is equal to the specimen thickness. J_{nom} is a useful quantity because it is the J value that would be assumed if a crack were found in a pipe, since the angle of inclination of the crack plane would be unknown from surface observations alone. Figure 2.8 shows the same results as Figure 2.6, but expressed as J_{nom} instead of $J_{tot}^{(a)}$. Here it is seen that use of J_{nom} does not necessarily eliminate the minimum in the toughness-versus-orientation curve.

All of the experiments described in the last paragraph employed side-grooved specimens. In Reference 2.10, Miglin reported tests on the same plate of ASTM A710 steel that Schroth used, but using plane-sided specimens. Miglin found that the geometry of crack growth was complex and depended on heat treatment. Of particular interest to the present program were observations of crack growth accompanied by crack plane rotation towards a plane of weakness, which contained clustering of elongated inclusions in the A710 steel. These experiments are germane to the present work because weld fusion lines also involve structural heterogeneities. If the precrack is placed close to the fusion line, the growing crack might be expected to 'seek out' the low toughness region of the weldment as it grows. Thus, the slant-notch specimen is useful in two situations:

- (1) Homogeneous materials where fracture occurs along inclined planes.
- (2) heterogeneous materials where planes of weakness are inclined at an angle to the principal normal stress.

In both situations, the slant-notch specimen is a promising method for evaluating LBB requirements to assess the lowest toughness region of the material as required by NRC's Standard Review Plan 3.6.3.

2.3.2 Procedures

The test procedures for the modified compact specimen shown in Figure 2.5 are described in detail by Manoharan, and others (Ref. 2.3). The specimen has the capability of measuring both Mode-I and Mode-III toughness components simultaneously. It was originally developed to overcome the shortcomings of combined torsion and tension, the alternative method of obtaining such data. Not only are experimental procedures for the modified compact specimen simpler, but the design also allows for determination of mixed-mode J-R curves, since significant amounts of crack growth can be monitored.

Preliminary test-procedure evaluation was performed using four specimens of austenitic stainless steel base metal from Pipe DP2-F33, two with flat notches and two with slant notches. In addition, five compact specimens were machined from each of the two welds that were fabricated and tested. The flat-notch specimens (Weld DP2-A53W1) were of standard compact design with the notch in the L-C orientation in order to simulate the circumferential through-wall crack of a pipe test, while the slant-notch specimens (Weld A8W4) were designed according to the sketch in Figure 2.5.

(a) $J_{nom} = J_{tot}/\sin \theta$, where θ = angle between the crack and the broad face of the specimen.

Table 2.5 Compact specimen dimensions

Specimen No.DP2-	Notch Orientation	Width, mm (in)	Thickness, mm (in)	Crack Length, mm (in)
<u>TP304 base metal crack location</u>				
F33-4-SS-1	Flat	51.0 (2.007)	25.5 (1.005)	28.8 (1.133)
F33-4-SS-2	Flat	51.0 (2.007)	25.4 (1.000)	28.5 (1.123)
F33-4-SSS-1	Slant	51.2 (2.016)	21.4 (0.842)	26.7 (1.050)
F33-4-SSS-2	Slant	50.9 (2.005)	21.4 (0.841)	26.5 (1.044)
<u>SAW Single-Vee fusion-line crack location</u>				
A8W4-FL-1	Slant	50.7 (1.998)	17.8 (0.702)	26.0 (1.025)
A8W4-FL-2	Slant	50.7 (1.999)	17.7 (0.699)	26.0 (1.025)
A8W4-FL-3	Slant	50.8 (2.000)	17.6 (0.694)	26.7 (1.053)
A8W4-FL-5	Slant	50.7 (1.996)	17.7 (0.698)	25.8 (1.017)
<u>SAW Slant-Vee fusion-line crack location</u>				
A53W1-FL-1	Flat	51.1 (2.011)	17.1 (0.675)	26.6 (1.046)
A53W1-FL-2	Flat	50.9 (2.006)	17.4 (0.685)	26.6 (1.048)
A53W1-FL-3	Flat	50.7 (1.998)	17.1 (0.675)	26.6 (1.048)
A53W1-FL-4	Flat	50.8 (2.000)	17.2 (0.676)	26.8 (1.056)
A53W1-FL-5	Flat	50.7 (1.998)	17.1 (0.674)	26.6 (1.049)

Each starter notch was machined so that the tip of the fatigue precrack would lie along the fusion line of the weld. However, the irregularities in the fusion line made it difficult to satisfy this requirement exactly. In order to more closely approximate piping, none of the specimens were side-grooved. Dimensions of the compact specimens are given in Table 2.5. Note that the preliminary-test specimens (DP2-F33-4 series) had different thicknesses; the slant-notch specimens were thinner than the flat-notch specimens so that the crack fronts would be the same length in both geometries.

All specimens were tested at 288 C (550 F) in displacement control in a screw-driven machine having a capacity of 225 kN (50,000 lb). The crosshead speed was 0.021 mm/sec (0.05 in/min) and was intended to cause crack initiation in four to seven minutes. In principle, four measurements are required for evaluation of both Mode-I and Mode-III components of J: load, displacement parallel to the load line, out-of-plane displacement, and crack growth. However, the out-of-plane displacement tends to be negligible if the specimen thickness is sufficiently large relative to the face dimensions. Independent post-mortem measurements demonstrated that this was the case for the designs used in the experiments reported here.

The electric potential method was used to indicate the point of crack initiation and the amount of crack extension. A modified procedure was used in which polarity was periodically reversed in order to account for possible zero drift. The data reduction software was also modified to accommodate this change.

The point of crack initiation was estimated from the electric potential, U . To achieve this estimate, graphs of U versus load-line displacement were examined for points of slope change. Engineering judgment was then used to estimate the value of U at crack initiation, U_0 . Crack growth beyond initiation was calculated from the ratio U/U_0 using the Johnson expression as given in Reference 2.11. Note that the term for the spacing of the voltage probes in the Johnson expression was allowed to increase in proportion to load-line displacement as the test progressed, because experience has shown that this procedure provides a more accurate estimate of crack growth in ductile materials as shown in Reference 2.12. Each test was terminated when the crack had extended by an amount equal to 40 to 55 percent of the original ligament. The total elapsed time for each test was approximately six to thirteen minutes. Note the data reduction procedure makes a linear correction on the crack growth difference between the electric potential calculated and final measured crack length, so that the final value in the J-R curve data is the final measured value.

The procedures used to calculate J values from each compact specimen test on flat-notch specimens were those specified in ASTM E1152-87, Standard Test Method for Determining J-R Curves^(a). Several values of J were calculated for slant-notch specimens. The initial calculation was of a quantity designated J_{nom} , which was defined as the value of J that the specimen would have if it were flat notched. Because there were no out-of-plane displacements, the analysis of Manoharan, and others, in Reference 2.3, provides simple relations for the individual components of J:

$$J_i = J_{nom}(\sin^3\theta) = 0.550J_{nom} \quad (2.3)$$

$$J_{iii} = J_{nom}\sin\theta(\cos^2\theta) = 0.269J_{nom} \quad (2.4)$$

$$J_{tot} = J_i + J_{iii} = 0.819J_{nom} \quad (2.5)$$

where J_{nom} is the value of J calculated using measured load and displacement with the assumption that the crack is normal to the broad face of the specimen. The above equations for the individual components of J are derived for a 55-degree angle between the specimen face and the crack plane and no out-of-plane displacements, as was the case for the slant-notch specimen experiments.

Figure 2.9 shows the individual components of the J-R curves for the stainless steel safe end, DP2-F33. The solid points are for a flat-notch specimen, while the open points are for a

(a) Although ASTM is in the process of combining E813 and E1152 into a unified standard, these experiments were carried out using guidelines from the standard in force at the time. We believe that use of the new standard would not significantly change any of the information in this report.

Figure 2.9 Comparison of toughness parameters for the slant-notch specimens

Figure 2.10 J-resistance curves for flat- and slant-notch specimens
[limit on J-R curve data is $\Delta a \leq 0.3(W-a_0)$]

slant-notch specimen. As noted above, J_{nom} is the value of J calculated from load and displacement using the thickness as the breadth of the crack front. Because loads and displacements are not resolved on the crack plane, J_{nom} is always the largest toughness value calculated from a slant-notch specimen for a 55-degree crack angle. Conversely, the actual J components, J_I and J_{III} , are the lowest values of J . J_{tot} can be thought of in two ways, as the total of the Mode-I and Mode-III components or as the value of J_{nom} resolved on the crack plane.

When applying the equations in this section to fusion lines, it should be kept in mind that they are analytically based for a homogeneous material. The actual situation at the crack tip includes constraint and triaxiality effects due to the overmatched nature of the welds. However, it is believed that this effect of constraint and triaxiality would not have a large effect on the conclusions because the same constraint and triaxiality effects will occur in a pipe girth weld with a fusion line crack.

2.3.3 Results

Table 2.6 summarizes the initiation J and dJ/da results; the detailed specimen data (load, displacement, crack growth, J_I , J_{III} , J_{tot} , and J_{nom} values) are in Appendix A.

2.3.3.1 TP304 Base Metal Experiments (Steel DP2-F33-4)

Figure 2.10 shows the crack-growth data expressed as J_{nom} , the value of J calculated as if all specimens had flat notches. While the data for the two flat-notch specimens agree quite well with one another, there is a discrepancy in the slant-notch data. Data for one of the slant-notch specimens lie along the lower edge of the flat-notch data, while the toughness of the other slant-notch specimen is about 600 kJ/m² (3,426 in-lb/in²) below that level. The difference between the two slant-notch specimens is believed to be associated with crack initiation since their crack growth curves are essentially parallel. Note: the Δa value of $0.3(W-a_0)$ has been found to be the limit of useable J-R curve data in the past, see Reference 2.13.

In comparison with other steels studied previously, the stainless steel slant-notch data most resemble those for the 'Super-Clean' ferritic steel in Figure 2.7 in that both of the J components in mixed-mode loading for the stainless steel are significantly less than the J levels for flat specimens. A closer comparison to 'Super-Clean' is seen in Figure 2.11, which suggests that the extrapolated J_{IIIc} of approximately 40 percent of J_{Ic} is similar for the two steels provided the linear relation of Figure 2.7 holds for the stainless steels tested here. As a result, k (from Equation 2.2) = 2.5. Such a high value of k suggests a large degree of shear sensitivity and the occurrence of a minimum value of J below J_{Ic} . This stainless steel violates the Kamat-Hirth criterion of Reference 2.9, since $J_{Ic}/\sigma_y = 14.5$ mm (0.57 inch); thus, it is not yet possible to predict mixed-mode behavior for all steels using their criterion.

DP2-F33-4 was the first austenitic steel tested using the technique of Manoharan, and others, as described in Reference 2.3 and the first to be tested at high temperatures. The behavior of the steel was reasonably comparable to the tough steels tested by Schroth (Ref. 2.5) and by Raghavachary (Ref. 2.6), giving support to the experimental technique chosen for this program.

Table 2.6 Summary of compact specimen data^(a)

Specimen No. DP2-	Notch Orientation	J at Initiation, kN/m (lb/in)	Initial dJ/da, MPa (ksi)
<u>TP304 base metal crack location</u>			
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)
<u>SAW single-Vee fusion-line crack location</u>			
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)
<u>SAW slant-Vee fusion-line crack location</u>			
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 2.11 Mixed-mode failure envelope for stainless steel safe end DP2-F33

2.3.3.2 Flat-Notch Fusion-Line Experiments (Weld DP2-A53W1)

Figure 2.12 shows the load/displacement curves for five nominally identical specimens. It was found that crack initiation occurred near maximum load in all cases.

The J-resistance curves associated with the flat-notch fusion-line specimens are unusual, as illustrated by Figure 2.13. The graph shows a large discrepancy in initiation toughness but a convergence of J values as the crack grows. The most striking observation is the toughness decrease with increasing crack growth of Specimen DP2-A53W1-FL-2. Here the crack tip was in the base metal, but the crack then grew to the fusion line. The data in Figure 2.13 show the need for replicate specimens when doing fusion line testing. For this fusion line only two of the five specimens (DP2-A53W-FL-1 and -4) exhibited what is believed to be lower bound behavior and these are the only specimens where the initial crack tip was on the fusion line. The other three specimens have much higher initiation toughness, but dJ/da becomes negative. For Specimen DP2-A53W1-FL-2, the initiation toughness is the highest, but dJ/da is negative immediately after crack initiation. With large amounts of crack growth, all the specimens seem to be approaching an asymptotic value around $1,300 \text{ kJ/m}^2$ ($7,423 \text{ in-lb/in}^2$).

The appearance of the specimens reflects the differences in initiation toughness of the DP2-A53W1 series. Fracture surfaces are shown in Figure 2.14 and it is seen that the low-initiation-toughness specimen (DP2-A53W1-FL-1) has a relatively normal appearance while the high-initiation-toughness specimen (DP2-A53W1-FL-2) exhibits asymmetric irregular crack growth.

Figure 2.12 Load-displacement curves for flat-notch, fusion-line specimens

Figure 2.13 J-resistance curves for flat-notch, fusion-line specimens from DP2-A53W
[limit on J-R curve data is $\Delta a \leq 0.3(W-a_0)$]

(a) Specimen DP2-A53W1-FL-1 (lowest toughness)

(b) Specimen DP2-A53W1-FL-2 (highest toughness)

Figure 2.14 Fracture surfaces of flat-notch specimens (Note: less crack growth on side adjacent to the TIG weld root passes.)

The differences are also seen in the profiles, illustrated by Figure 2.15. The low-initiation-toughness specimen (DP2-A53W1-FL-1) has a relatively flat fracture path that lies within the weld metal, while the crack in the high-initiation-toughness specimen (DP2-A53W1-FL-2) starts in the base metal and diverts out of the crack plane until it reaches the fusion line at which time dJ/da becomes negative.

2.3.3.3 Slant-Notch Fusion-Line Experiments (Weld DP2-A8W4)

Figure 2.16 shows that the load/displacement curves for these slant-notch specimens were reasonably reproducible. Unexplained sudden load drops occurred during testing of Specimens A8W4-FL-3 and A8W4-FL-5. (Test problems occurred for Specimen A8W4-FL-4, and hence these data are not provided.) The J-R curves were also quite reproducible, as shown in Figure 2.17. Note that the load drop for Specimen A8W4-FL-5 corresponded to a crack jump as seen in the J-R curve. The load drop for Specimen A8W4-FL-3 was smaller and the crack jump is not evident in the J-R curve. The curves in Figure 2.17 are reminiscent of the intermediate curves of the slant-Vee weld (see Fig. 2.13) in that they are essentially flat; almost all of the data for crack growths greater than 2 mm (0.079 inch) lie between J values of 800 and 1,200 kJ/m^2 (4,568 and 6,852 in-lb/in^2). There appears to be a steady-state J value between 900 and 1,100 kJ/m^2 (5,139 in-lb/in^2 and 6,281 in-lb/in^2), which is slightly lower than the 1,300 kJ/m^2 (7,423 in-lb/in^2) asymptotic value from the DP2-A53W1 flat-notch fusion-line specimens. Figure 2.18 shows that the crack was, indeed, very close to the fusion line, but actually propagated in the weld metal a small distance from the fusion line. Hence, it may have been better to place the notch at this location to test the least-fracture-resistant plane.

Figure 2.19 compares the J-R curves for the base metal, the weld metal, and the fusion line. There is a scatter band for the fusion line because the k parameter in the failure criterion, Equation 2.2, cannot be determined when experiments are conducted at only one angle. Values of $k = 0$ and 1 have been arbitrarily chosen as bounds for the data. It is seen that the weld is the low toughness component of the weldment until about 10 mm (0.394 inch) of crack growth, at which point the weld metal and fusion line have roughly comparable toughnesses. It is possible that the dJ/da of the weld is positive; whereas, for the fusion line dJ/da it is close to zero. This observation suggests that further crack growth might occur along the fusion line.

2.4 Discussion on Integration of Specimen Test Results with Past Results

The experiments presented above show that the slant-notch technique works well at elevated temperatures and on fusion lines. They also present evidence that flat-notch toughness may be higher than when the crack plane is inclined.

There are problems illuminated by the flat-notch specimens, however. Unlike the slant-notch specimens, these specimens exhibit large scatter at initiation. While this scatter decreases with increasing crack growth (Figure 2.13), it still persists after 8 mm (0.315 inch) of growth.

There seems to be a higher steady-state J value, J_{ss} , for Weld DP2-A53W1 than for Weld DP2-A8W4 by about 30 percent. However, the Charpy data (Table 2.4) show the flat-notch fusion

(a) Specimen DP2-A53W1-FL-1 (3X); low initiation toughness in weld metal near fusion line

(b) Specimen DP2-A53W1-FL-2 (3X); high initiation toughness in base metal near fusion line

Figure 2.15 Low magnification profiles of centerlines of flat-notch, fusion line specimens to illustrate importance of precise crack-tip location on initiation toughness

Figure 2.16 Load-displacement curves of slant-notch, fusion-line specimens
(Note: There were sudden load drops in Specimens A8W4-FL-3 and -5.)

Figure 2.17 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 2.18 High-magnification (100X) profile of slant-notch, fusion-line
Specimen DP2-A8W-1

Figure 2.19 Comparison of J_{nom} resistance curves for base metal, weld, and fusion line

line (DP2-A53W1) to have about a factor of 5 higher impact energy than the slant-notch fusion line (DP2-A8W4), a result at variance with the compact specimen data. There are three possible reasons for Charpy-specimen data not mirroring those of compact specimens:

- (1) High loading rate.
- (2) Use of a notch instead of a crack.
- (3) Low constraint.

Since stainless steel is not highly sensitive to loading rate at 288 C (550 F), Ref. 2.12, the high loading rate argument does not hold. Use of a blunter notch, rather than a sharp crack, spreads out the stress field, so that the resulting crack can pick out the fracture path of least resistance. However, it is difficult to see how this factor can explain the results. The constraint explanation is even more difficult to assess because of the additional constraint due to weld mismatch (both weldments appeared to have the same degree of overmatching strength, judging from the hardness results in Table 2.2). As a result, the reason that the Charpy specimen does not provide a good screening test is unresolved. The practical effect was that the ASME Section XI Charpy energy versus J_{1mm} correlation was very conservative and could not be used to estimate toughness accurately. Also, to determine the steady-state J-R curve value, there is a great degree of conservatism in the ASME J_{1mm} values. Hence, to take advantage of this conservatism the J_{ss} value would have to be developed from compact specimen experiments.

The crack growth resistance of the fusion line appeared to reach a steady-state value, while the SAW J-R curve had an increasing J-R curve. Figure 2.20, which came from Degraded Piping Program

Figure 2.20 J_D -R curves for austenitic SAW C(T) specimens of various planform sizes (Ref. 2.14)

experiments, Ref. 2.14, also shows an increasing J-R curve. The C(T) specimens in Figure 2.20 were all 25.4-mm (1.0-inch) thick. In checking the fracture surface on the 9.5T C(T) specimen (still in the Battelle specimen archive room), it was found that during the initial 38 to 51 mm (1.5 to 2.0 inches) of growth, the crack was in the weld metal, but then later turned into the fusion line. Hence, with the larger C(T) specimen, the SAW J_D -R curve continued to increase with larger amounts of crack growth than that shown in Figure 2.19. It is unclear whether the growth into the fusion line caused the 9.5T C(T) specimen J-R curve to decrease in slope or whether the decrease was due to approaching the crack growth limit of 30 percent of the initial ligament [72.4 mm (2.85 inch)] as suggested in Reference 2.13. This result suggests that to ensure conservatism for stainless steel welds with cracks close to the fusion line, the weld metal J-R curve should be used up to the point of the fusion-line steady-state value. Large C(T) specimen tests (such as those done in Reference 2.14) with the initial crack in the fusion line would help to confirm this hypothesis.

An important implication of this work is that the toughness of wrought stainless steel fusion lines can be lower than the toughness from SAW or SMAW weld metal after small amounts of crack growth. The ASME austenitic pipe flaw evaluation criterion was the SAW and SMAW J-R curves. These Z-factors will be affected if calculated using the fusion-line toughness J-R curves established in this report. The Z-factors would probably increase for larger diameter pipe where there is more crack growth in the analysis. The magnitude of these changes to the Z-factors has not been determined in this report.

This effect of the wrought stainless steel fusion-line toughness reaching a steady-state value after a small amount of crack growth can also be important for LBB implications. It is anticipated that the same effect of a steady-state toughness in the fusion line may also exist for cast stainless steel welds, since the welding procedures are very similar. A question of the applicability of these results is whether cracks will form along the fusion line in cast stainless steel piping. IGSCC may not be as likely in the cast stainless steels, but weld fabrication defects (i.e., lack of side wall fusion) may occur. Hence, fusion line cracks can be relevant to cast stainless steel piping.

In regard to the lower fusion-line crack-tip-opening angle in Figure 1.6, the implication from the comparisons of the weld metal and fusion-line crack-tip-opening angles was that the fusion-line toughness was a factor of 3 less than that of the weld in that work. This difference in the fusion-line and weld-metal toughness was not observed in the work performed in this effort. A contributing factor may be the direction of crack growth. In the C(T) tests performed in this effort, the crack grew as a through-wall crack; whereas in the past work on the Figure 1.6 specimens, the crack was growing as a surface crack. Some tests in the through-thickness or radial direction with single-edge-notched specimens with smaller specimen thicknesses than used in the past study might help to clarify this discrepancy.

As a final note, it appears from the metallographic evaluations that the low fracture resistance path in these tests was actually in the weld metal about 0.1 mm (0.004 inch) from the fusion line. Hence, we may have seen more consistent results if we put the initial crack tip at that location, although frequently IGSCCs just stop at the fusion line. The fracture locations in these C(T) tests, however, appear to be more in the weld metal; whereas the metallographic sections in Figure 1.8 from a pipe experiment showed that the crack may propagate in either the fusion line or the weld metal, and

possibly also in the base metal close to the fusion line. Hence, there may be a composite toughness for such a case.

2.5 References

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3.0 SUMMARY AND CONCLUSIONS

From past data, and data developed in this program, several observations and conclusions can be made.

- (1) Measurements of the toughness in the fusion line with a sharp crack specimen are highly sensitive to the crack tip location relative to the fusion line. The plane of lowest fracture resistance was about 0.1 mm (0.004 inch) from the fusion line in the weld metal for these tests. Preferably, more replicate specimens than typically used for base metal tests should be tested for fusion line evaluations, and the specimens may require metallographic sectioning to explain any unusual results. This need for a greater number of specimens for fusion-line testing is not surprising. Perhaps the Charpy tests were more reproducible because it is easier to get the fusion line in the high stress region ahead of the blunt notch.
- (2) The energy values of the Charpy fusion-line specimens were more consistent than the C(T) specimen J_{Ic} values and gave the same relative ranking of the initiation toughness of the two welds evaluated; however, the consistency of the J_{Ic} data to Charpy energy data was not very good. The Charpy energy data at 288 C (550 F) showed that Weld DP2-A53W1 was 4.8 times tougher than Weld DP2-A8W4; whereas the C(T) specimen data showed that, for the valid specimens, the J_{Ic} of Weld DP2-A53W1 was 1.5 times tougher than Weld DP2-A8W4.
- (3) The J_{1mm} values calculated from the Charpy energy data using the ASME Section XI Appendix H, Ref. 3.1, correlation (see Table 3.1) were conservative for both fusion lines. Based on the mean values, the conservatism was extreme for both DP2-A8W4 and DP2-A53W1.

If the ASME Charpy energy correlation is to be used, it may be very conservative, e.g., by a factor of 9 in the case of Weld DP2-A8W4. The effect of this conservatism on estimating pipe failure loads was not investigated.

Table 3.1 Crack growth resistance parameters

Fusion Line Designation	J_{1mm} , kN/m (lb/in)		
	ASME Section XI Appendix H Charpy Estimate	Actual	J_{ss} , kN/m (lb/in)
DP2-A8W4	85 ± 5 (486 ± 29)	766 ± 150 (4372 ± 856)	1030 ± 117 (5890 ± 669)
DP2-A53W1	407 ± 72 (2325 ± 411)	1177 ± 806 (6724 ± 4603)	1321 ± 171 (7550 ± 977)

- (4) For the materials evaluated in this report, the initiation toughness of the stainless steel base metal was much higher than the SAW or the fusion line. The fusion line toughness J_{Ic} was greater than the SAW toughness.
- (5) A comparison of toughness values from slant-notch to flat-notch specimens generally requires two different angled notches. The two welds used, one for flat and one for slant notch specimens, had drastically different Charpy energies along their fusion lines. Hence, the effect of notch type on fusion-line toughness was clouded by the toughness variation between the welds.
- (6) The nominal mixed-mode toughness of the stainless steel base metal was significantly less than J_{Ic} . This result is consistent with the general behavior of steels illustrated in this report, where higher toughness leads to greater shear sensitivity. As a result, this orientation effect might cause a fusion-line crack to grow into the base metal near the weld.
- (7) The crack growth resistance of the fusion line appeared to reach a steady-state value, while the SAW J-R curve had an increasing J-R curve. This result suggests that to be conservative for stainless steel welds with cracks close to the fusion line, the weld metal J-R curve should be used up to the point of the fusion-line steady-state value; thereafter, the J-R curve should remain at the fusion-line steady-state J value. A large C(T) specimen test with the initial crack in the fusion line would help to confirm this hypothesis.
- (8) 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 tougher fusion line and produce a decreasing J-R curve as was seen with Specimen A53W1-FL-2. From our knowledge, such a decreasing toughness curve has never been observed when testing homogeneous specimens.
- (9) The final and 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 trying to rationalize the observed fracture behavior in Section 1 of this report, the apparent steady-state fusion-line toughness compared with the increasing weld metal J-R curve may explain why the cracks in many of the pipe tests grew out of the center of the weld and followed the fusion line. 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 toe of the weld crown where the thickness is less and where there is a slight stress concentration. It has also been observed that on the inside of the pipe, the crack will go to either the root of the weld or to the counterbore. The root 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, see Figure 1.8, the weld crown was removed, and the crack still followed the fusion line. Hence, the presence of a weld crown may have helped the crack turn to the fusion line, but perhaps, due to the lower crack growth resistance of the fusion line, the crack may have turned into the fusion line anyway. From these results it is concluded that the presence of the weld crown is not a sufficient condition to cause a crack to follow the fusion line.

Finally, in regard to the lower fusion-line crack-tip-opening angle in Figure 1.6, the implication from the comparisons of the weld metal and fusion-line crack-tip-opening angles was that the fusion-line toughness was a factor of 3 less than that of the weld in that work. This degree of difference in the fusion-line and weld-metal toughness was not observed in the work performed in this effort. A contributing factor may be the direction of crack growth. Some tests in the through-thickness or radial direction with single-edge-notched specimens might help to clarify this discrepancy.

3.1 References

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APPENDIX A

Detailed Data from C(T) Tests

Table A.1a J-resistance test data for Compact Specimen A53W1-FL-1
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J _D , kJ/m ²	J _M , kJ/m ²
0.000	0.000	26.561	0.000	0.0	0.0
11.325	0.223	26.561	0.000	7.3	7.3
26.765	0.620	26.561	0.000	47.4	47.4
27.308	0.657	26.561	0.000	52.7	52.7
29.123	0.868	26.561	0.000	84.2	84.2
30.355	1.141	26.561	0.000	127.2	127.2
31.020	1.389	26.561	0.000	167.5	167.5
31.331	1.526	26.561	0.000	190.0	190.0
31.906	1.798	26.561	0.000	235.6	235.6
32.118	1.922	26.561	0.000	256.6	256.6
32.325	2.282	26.561	0.000	318.0	318.0
32.427	2.468	26.561	0.000	349.9	349.9
32.473	2.592	26.561	0.000	371.2	371.2
32.545	2.915	26.561	0.000	426.7	426.7
32.527	3.138	26.561	0.000	465.1	465.1
32.512	3.200	26.561	0.000	475.8	475.8
32.512	3.200	26.561	0.000	475.8	475.8
32.318	3.460	26.752	0.191	515.1	520.0
32.181	3.584	26.874	0.313	532.7	540.9
31.679	3.894	27.179	0.618	576.0	593.2
31.191	4.130	27.398	0.837	608.6	632.7
30.884	4.266	27.542	0.981	626.5	655.4
30.329	4.552	27.873	1.312	661.9	702.4
29.947	4.812	28.122	1.561	695.5	745.3
29.681	4.973	28.300	1.739	715.0	771.8
29.248	5.234	28.597	2.036	745.3	814.3
28.265	5.631	29.006	2.445	791.5	878.4
27.919	5.730	29.132	2.571	801.6	894.2
26.917	6.027	29.581	3.020	826.5	940.4
26.267	6.226	29.915	3.354	840.4	970.8
25.264	6.635	30.414	3.853	876.7	1032.8
24.573	6.945	30.782	4.221	903.1	1079.2
24.113	7.131	31.028	4.467	916.8	1106.8
23.517	7.367	31.309	4.748	935.2	1141.5
22.677	7.677	31.737	5.176	954.0	1186.0
22.222	7.851	31.990	5.429	963.1	1210.6
21.515	8.136	32.357	5.796	979.8	1250.7
21.209	8.297	32.551	5.990	989.8	1273.3
20.733	8.558	32.885	6.325	1003.4	1309.2
20.358	8.793	33.176	6.615	1016.1	1341.7
19.911	9.054	33.453	6.892	1032.4	1377.6
19.492	9.277	33.691	7.130	1045.8	1408.1
18.994	9.488	33.948	7.387	1055.1	1436.4
18.269	9.835	34.354	7.793	1069.9	1482.0
17.750	10.108	34.615	8.055	1085.3	1517.8
17.528	10.232	34.737	8.176	1091.8	1534.0
16.796	10.579	35.134	8.573	1103.1	1577.8
16.254	10.778	35.441	8.880	1101.9	1602.1
15.851	10.902	35.632	9.071	1100.8	1617.2
15.485	11.013	35.801	9.241	1099.8	1630.6

Table A.1b J-resistance test data for Compact Specimen A53W1-FL-1
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J _D , $\frac{\text{inch-lb}}{\text{inch}^2}$	J _M , $\frac{\text{inch-lb}}{\text{inch}^2}$
0	0.0000	1.0457	0.0000	0	0
2517	0.0088	1.0457	0.0000	42	42
5948	0.0244	1.0457	0.0000	271	271
6069	0.0259	1.0457	0.0000	301	301
6472	0.0342	1.0457	0.0000	481	481
6746	0.0449	1.0457	0.0000	726	726
6893	0.0547	1.0457	0.0000	956	956
6963	0.0601	1.0457	0.0000	1085	1085
7090	0.0708	1.0457	0.0000	1345	1345
7137	0.0757	1.0457	0.0000	1465	1465
7183	0.0898	1.0457	0.0000	1816	1816
7206	0.0972	1.0457	0.0000	1998	1998
7216	0.1021	1.0457	0.0000	2119	2119
7232	0.1148	1.0457	0.0000	2436	2436
7228	0.1235	1.0457	0.0000	2656	2656
7225	0.1260	1.0457	0.0000	2717	2717
7225	0.1260	1.0457	0.0000	2717	2717
7182	0.1362	1.0532	0.0075	2941	2969
7151	0.1411	1.0580	0.0123	3042	3089
7040	0.1533	1.0700	0.0243	3289	3387
6931	0.1626	1.0786	0.0329	3475	3613
6863	0.1680	1.0843	0.0386	3577	3742
6740	0.1792	1.0974	0.0517	3779	4011
6655	0.1895	1.1072	0.0615	3971	4256
6596	0.1958	1.1142	0.0685	4083	4407
6500	0.2061	1.1259	0.0802	4256	4650
6281	0.2217	1.1420	0.0963	4519	5016
6204	0.2256	1.1469	0.1012	4577	5106
5982	0.2373	1.1646	0.1189	4719	5370
5837	0.2451	1.1777	0.1320	4799	5543
5614	0.2612	1.1974	0.1517	5006	5897
5461	0.2734	1.2119	0.1662	5157	6162
5358	0.2808	1.2216	0.1759	5235	6320
5226	0.2900	1.2326	0.1869	5340	6518
5039	0.3023	1.2495	0.2038	5447	6772
4938	0.3091	1.2594	0.2137	5499	6913
4781	0.3203	1.2739	0.2282	5594	7141
4713	0.3267	1.2815	0.2358	5652	7270
4607	0.3369	1.2947	0.2490	5730	7476
4524	0.3462	1.3061	0.2604	5802	7661
4425	0.3565	1.3170	0.2713	5895	7866
4332	0.3652	1.3264	0.2807	5971	8040
4221	0.3735	1.3365	0.2908	6025	8202
4060	0.3872	1.3525	0.3068	6109	8462
3944	0.3980	1.3628	0.3171	6197	8667
3895	0.4028	1.3676	0.3219	6234	8759
3733	0.4165	1.3832	0.3375	6299	9009
3612	0.4243	1.3953	0.3496	6292	9148
3522	0.4292	1.4028	0.3571	6286	9234
3441	0.4336	1.4095	0.3638	6280	9311

Table A.2a J-resistance test data for Compact Specimen A53W1-FL-2
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J _D , kJ/m ²	J _M , kJ/m ²
0.000	0.000	26.617	0.000	0.0	0.0
26.657	0.818	26.617	0.000	59.5	59.5
29.552	1.631	26.617	0.000	179.5	179.5
31.298	2.469	26.617	0.000	313.4	313.4
32.669	3.274	26.617	0.000	448.7	448.7
33.882	4.069	26.617	0.000	587.6	587.6
34.961	4.892	26.617	0.000	736.4	736.4
35.569	5.705	26.617	0.000	886.9	886.9
35.938	6.510	26.617	0.000	1038.1	1038.1
35.833	7.300	26.617	0.000	1186.9	1186.9
35.701	8.161	26.617	0.000	1348.7	1348.7
35.780	8.961	26.617	0.000	1498.8	1498.8
35.886	9.705	26.617	0.000	1638.9	1638.9
35.780	10.640	26.617	0.000	1814.7	1814.7
35.543	11.349	26.617	0.000	1947.5	1947.5
34.093	12.118	26.617	0.000	2088.2	2088.2
32.827	12.266	26.908	0.292	2079.3	2112.8
31.983	12.416	27.198	0.581	2070.4	2137.4
30.823	12.576	27.748	1.131	2030.7	2161.4
30.032	12.738	28.183	1.567	2005.3	2186.4
29.057	12.911	28.508	1.891	1994.6	2213.4
28.213	13.096	29.072	2.455	1955.7	2240.2
27.685	13.259	29.462	2.846	1934.6	2264.5
27.369	13.419	29.774	3.157	1922.7	2288.9
26.657	13.581	30.148	3.531	1903.1	2313.2
26.104	13.754	30.447	3.830	1894.1	2339.4
24.996	13.927	30.871	4.255	1868.7	2364.2
24.680	14.102	31.251	4.634	1848.8	2389.3
24.179	14.275	31.613	4.997	1830.6	2414.2
23.783	14.448	31.964	5.347	1813.6	2439.1
23.414	14.623	32.373	5.757	1789.2	2463.8
23.098	14.808	32.696	6.080	1777.4	2490.9
22.676	15.006	33.123	6.507	1753.9	2519.1
22.122	15.192	33.508	6.891	1733.6	2545.5
21.595	15.380	33.922	7.305	1709.3	2571.8
21.199	15.565	34.276	7.659	1692.4	2598.3
20.751	15.751	34.778	8.161	1655.3	2622.9
20.382	15.949	35.151	8.534	1637.5	2651.2
20.039	16.137	35.609	8.993	1606.2	2676.7
19.723	16.347	35.982	9.365	1590.2	2707.1
19.433	16.546	36.427	9.810	1561.9	2734.5
19.116	16.744	36.788	10.171	1545.2	2763.1
18.774	16.942	37.175	10.558	1524.5	2791.5
18.536	17.140	37.450	10.833	1519.3	2821.4
18.246	17.338	37.869	11.252	1493.1	2849.2
17.824	17.562	38.260	11.643	1474.9	2881.8

Table A.2b J-resistance test data for Compact Specimen A53W1-FL-2
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J_D , $\frac{\text{inch-lb}}{\text{inch}^2}$	J_M , $\frac{\text{inch-lb}}{\text{inch}^2}$
0	0.0000	1.0479	0.0000	0	0
5924	0.0322	1.0479	0.0000	340	340
6567	0.0642	1.0479	0.0000	1025	1025
6955	0.0972	1.0479	0.0000	1790	1790
7260	0.1289	1.0479	0.0000	2562	2562
7529	0.1602	1.0479	0.0000	3355	3355
7769	0.1926	1.0479	0.0000	4205	4205
7904	0.2246	1.0479	0.0000	5064	5064
7986	0.2563	1.0479	0.0000	5927	5927
7963	0.2874	1.0479	0.0000	6777	6777
7934	0.3213	1.0479	0.0000	7701	7701
7951	0.3528	1.0479	0.0000	8558	8558
7975	0.3821	1.0479	0.0000	9358	9358
7951	0.4189	1.0479	0.0000	10362	10362
7898	0.4468	1.0479	0.0000	11120	11120
7576	0.4771	1.0479	0.0000	11923	11923
7295	0.4829	1.0594	0.0115	11873	12064
7107	0.4888	1.0708	0.0229	11822	12205
6850	0.4951	1.0924	0.0445	11595	12342
6674	0.5015	1.1096	0.0617	11450	12484
6457	0.5083	1.1224	0.0745	11389	12639
6270	0.5156	1.1446	0.0967	11167	12791
6152	0.5220	1.1599	0.1120	11047	12930
6082	0.5283	1.1722	0.1243	10979	13070
5924	0.5347	1.1869	0.1390	10867	13208
5801	0.5415	1.1987	0.1508	10815	13358
5555	0.5483	1.2154	0.1675	10670	13499
5484	0.5552	1.2303	0.1824	10557	13643
5373	0.5620	1.2446	0.1967	10453	13785
5285	0.5688	1.2584	0.2105	10355	13927
5203	0.5757	1.2745	0.2266	10216	14069
5133	0.5830	1.2873	0.2394	10149	14223
5039	0.5908	1.3041	0.2562	10015	14384
4916	0.5981	1.3192	0.2713	9899	14535
4799	0.6055	1.3355	0.2876	9760	14685
4711	0.6128	1.3494	0.3015	9664	14836
4611	0.6201	1.3692	0.3213	9452	14977
4529	0.6279	1.3839	0.3360	9350	15138
4453	0.6353	1.4019	0.3540	9172	15284
4383	0.6436	1.4166	0.3687	9080	15457
4318	0.6514	1.4341	0.3862	8919	15614
4248	0.6592	1.4483	0.4004	8823	15778
4172	0.6670	1.4636	0.4157	8705	15939
4119	0.6748	1.4744	0.4265	8675	16110
4055	0.6826	1.4909	0.4430	8526	16269
3961	0.6914	1.5063	0.4584	8422	16455

Table A.3a J-resistance test data for Compact Specimen A53W1-FL-3
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J _D , kJ/m ²	J _M , kJ/m ²
0.000	0.000	26.612	0.000	0.0	0.0
25.101	0.549	26.612	0.000	37.4	37.4
28.319	1.064	26.612	0.000	111.4	111.4
29.848	1.570	26.612	0.000	190.3	190.3
31.008	2.078	26.612	0.000	273.3	273.3
31.983	2.611	26.612	0.000	363.5	363.5
32.827	3.119	26.612	0.000	452.0	452.0
33.539	3.609	26.612	0.000	539.3	539.3
34.330	4.168	26.612	0.000	641.2	641.2
34.884	4.663	26.612	0.000	733.2	733.2
35.358	5.166	26.612	0.000	828.1	828.1
35.701	5.679	26.612	0.000	926.0	926.0
36.097	6.269	26.612	0.000	1039.6	1039.6
36.308	6.741	26.612	0.000	1131.4	1131.4
36.492	7.300	26.612	0.000	1240.7	1240.7
36.308	7.727	26.612	0.000	1324.1	1324.1
36.097	7.831	26.673	0.062	1339.6	1344.1
34.963	8.174	27.030	0.418	1377.2	1408.2
34.488	8.415	27.331	0.720	1398.4	1452.7
33.645	8.656	27.650	1.038	1417.3	1496.7
32.774	9.009	27.954	1.342	1456.8	1561.0
32.484	9.271	28.256	1.644	1478.4	1607.9
32.115	9.563	28.526	1.915	1507.8	1660.8
31.720	9.830	28.780	2.168	1533.5	1708.9
31.034	10.140	29.118	2.507	1557.9	1764.2
30.507	10.424	29.421	2.809	1580.1	1814.7
30.032	10.709	29.710	3.098	1602.7	1865.0
29.426	10.988	30.028	3.417	1620.3	1913.9
28.767	11.293	30.382	3.770	1637.6	1966.7
28.345	11.440	30.664	4.052	1633.6	1991.6
27.738	11.732	31.013	4.401	1647.5	2041.6
27.132	12.029	31.363	4.752	1660.9	2092.1
26.447	12.352	31.730	5.119	1675.5	2146.6
25.919	12.662	32.111	5.499	1685.1	2198.3
25.339	12.850	32.391	5.780	1684.6	2229.4
24.390	13.195	32.877	6.266	1684.6	2285.1
23.335	13.531	33.327	6.716	1685.4	2338.4
22.623	13.693	33.659	7.048	1670.8	2363.2
21.515	14.064	34.180	7.568	1664.5	2419.3
21.015	14.237	34.535	7.924	1646.4	2444.5
20.118	14.585	35.003	8.392	1640.2	2496.0
19.195	14.945	35.644	9.032	1609.9	2545.9
18.879	15.143	35.952	9.340	1599.6	2574.5
17.903	15.527	36.540	9.928	1577.2	2627.7
17.482	15.725	36.867	10.256	1562.3	2655.3
17.007	15.913	37.179	10.567	1547.6	2681.4
15.979	16.335	37.739	11.127	1530.1	2738.4
15.478	16.533	38.046	11.434	1515.1	2765.0
14.819	16.929	38.580	11.968	1493.3	2816.5

Table A.3b J-resistance test data for Compact Specimen A53W1-FL-3
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	$J_D,$ $\frac{\text{inch-lb}}{\text{inch}^2}$	$J_M,$ $\frac{\text{inch-lb}}{\text{inch}^2}$
0	0.0000	1.0477	0.0000	0	0
5578	0.0216	1.0477	0.0000	213	213
6293	0.0419	1.0477	0.0000	636	636
6633	0.0618	1.0477	0.0000	1087	1087
6891	0.0818	1.0477	0.0000	1561	1561
7107	0.1028	1.0477	0.0000	2076	2076
7295	0.1228	1.0477	0.0000	2581	2581
7453	0.1421	1.0477	0.0000	3079	3079
7629	0.1641	1.0477	0.0000	3661	3661
7752	0.1836	1.0477	0.0000	4187	4187
7857	0.2034	1.0477	0.0000	4728	4728
7934	0.2236	1.0477	0.0000	5287	5287
8022	0.2468	1.0477	0.0000	5936	5936
8068	0.2654	1.0477	0.0000	6460	6460
8109	0.2874	1.0477	0.0000	7084	7084
8068	0.3042	1.0477	0.0000	7560	7560
8022	0.3083	1.0501	0.0024	7649	7675
7770	0.3218	1.0642	0.0165	7864	8041
7664	0.3313	1.0760	0.0283	7985	8295
7477	0.3408	1.0886	0.0409	8093	8546
7283	0.3547	1.1005	0.0528	8318	8913
7219	0.3650	1.1124	0.0647	8441	9181
7137	0.3765	1.1231	0.0754	8610	9483
7049	0.3870	1.1331	0.0854	8756	9758
6897	0.3992	1.1464	0.0987	8896	10073
6779	0.4104	1.1583	0.1106	9022	10362
6674	0.4216	1.1697	0.1220	9151	10649
6539	0.4326	1.1822	0.1345	9252	10928
6393	0.4446	1.1961	0.1484	9351	11230
6299	0.4504	1.2072	0.1595	9328	11372
6164	0.4619	1.2210	0.1733	9407	11657
6029	0.4736	1.2348	0.1871	9483	11946
5877	0.4863	1.2492	0.2015	9567	12257
5760	0.4985	1.2642	0.2165	9622	12552
5631	0.5059	1.2753	0.2276	9619	12730
5420	0.5195	1.2944	0.2467	9619	13048
5186	0.5327	1.3121	0.2644	9623	13352
5027	0.5391	1.3252	0.2775	9540	13494
4781	0.5537	1.3457	0.2980	9504	13814
4670	0.5605	1.3597	0.3120	9401	13958
4471	0.5742	1.3781	0.3304	9366	14252
4266	0.5884	1.4033	0.3556	9192	14537
4195	0.5962	1.4154	0.3677	9134	14700
3979	0.6113	1.4386	0.3909	9006	15004
3885	0.6191	1.4515	0.4038	8921	15162
3779	0.6265	1.4637	0.4160	8837	15311
3551	0.6431	1.4858	0.4381	8737	15636
3440	0.6509	1.4979	0.4502	8651	15788
3293	0.6665	1.5189	0.4712	8527	16082

Table A.4a J-resistance test data for Compact Specimen A53W1-FL-4
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J _D , kJ/m ²	J _M , kJ/m ²
0.000	0.000	26.825	0.000	0.0	0.0
14.950	0.229	26.825	0.000	9.3	9.3
23.256	0.462	26.825	0.000	33.4	33.4
25.972	0.693	26.825	0.000	64.1	64.1
27.527	0.927	26.825	0.000	97.8	97.8
28.424	1.151	26.825	0.000	131.5	131.5
29.215	1.377	26.825	0.000	166.7	166.7
29.927	1.626	26.825	0.000	206.4	206.4
30.428	1.836	26.825	0.000	240.7	240.7
30.955	2.078	26.825	0.000	280.6	280.6
31.351	2.301	26.825	0.000	318.2	318.2
31.667	2.525	26.825	0.000	356.2	356.2
31.983	2.753	26.825	0.000	395.4	395.4
32.194	2.990	26.825	0.000	436.3	436.3
32.353	3.193	26.825	0.000	471.7	471.7
32.511	3.411	26.825	0.000	509.9	509.9
32.590	3.566	26.906	0.081	534.7	536.9
32.669	3.894	27.124	0.299	585.4	594.1
32.669	4.247	27.380	0.555	639.2	656.3
32.643	4.569	27.620	0.795	687.9	713.6
32.142	4.917	27.893	1.068	739.0	775.4
31.904	5.227	28.198	1.373	780.8	830.1
31.509	5.502	28.486	1.661	816.4	878.5
30.902	5.834	28.759	1.934	862.1	937.3
30.111	6.190	29.174	2.349	902.5	998.8
29.479	6.480	29.507	2.682	934.3	1048.6
28.819	6.840	29.858	3.033	976.2	1110.3
27.976	7.181	30.266	3.442	1008.9	1167.5
27.396	7.447	30.581	3.756	1033.7	1212.0
26.367	7.831	31.092	4.267	1062.9	1274.4
25.524	8.131	31.465	4.640	1085.9	1322.8
24.917	8.415	31.818	4.993	1106.4	1368.2
24.416	8.793	32.218	5.393	1137.3	1428.5
23.941	9.108	32.514	5.689	1165.1	1478.8
23.414	9.408	32.822	5.997	1188.1	1526.2
22.570	9.741	33.296	6.471	1200.2	1577.1
21.911	10.058	33.669	6.844	1217.5	1625.7
21.041	10.429	34.218	7.393	1224.4	1680.4
20.329	10.772	34.573	7.748	1244.0	1731.8
19.828	11.006	34.800	7.975	1257.8	1766.7
19.063	11.397	35.512	8.688	1243.7	1819.9
18.615	11.659	35.624	8.799	1272.4	1859.5
17.798	12.055	36.235	9.410	1265.2	1913.3
17.429	12.304	36.552	9.727	1267.8	1948.3
16.848	12.614	36.923	10.098	1272.4	1991.6
16.242	13.035	37.452	10.627	1272.7	2048.7
15.688	13.332	37.820	10.995	1272.7	2089.2
15.135	13.630	38.164	11.339	1274.2	2129.5
14.396	14.077	38.641	11.816	1278.2	2188.8

Table A.4b J-resistance test data for Compact Specimen A53W1-FL-4
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J_D , $\frac{\text{inch-lb}}{\text{inch}^2}$	J_M , $\frac{\text{inch-lb}}{\text{inch}^2}$
0	0.0000	1.0561	0.0000	0	0
3322	0.0090	1.0561	0.0000	53	53
5168	0.0182	1.0561	0.0000	191	191
5772	0.0273	1.0561	0.0000	366	366
6117	0.0365	1.0561	0.0000	558	558
6316	0.0453	1.0561	0.0000	751	751
6492	0.0542	1.0561	0.0000	952	952
6650	0.0640	1.0561	0.0000	1178	1178
6762	0.0723	1.0561	0.0000	1374	1374
6879	0.0818	1.0561	0.0000	1602	1602
6967	0.0906	1.0561	0.0000	1817	1817
7037	0.0994	1.0561	0.0000	2034	2034
7107	0.1084	1.0561	0.0000	2258	2258
7154	0.1177	1.0561	0.0000	2491	2491
7190	0.1257	1.0561	0.0000	2693	2693
7225	0.1343	1.0561	0.0000	2912	2912
7242	0.1404	1.0593	0.0032	3053	3066
7260	0.1533	1.0679	0.0118	3343	3392
7260	0.1672	1.0779	0.0218	3650	3748
7254	0.1799	1.0874	0.0313	3928	4075
7143	0.1936	1.0982	0.0421	4220	4427
7090	0.2058	1.1101	0.0540	4459	4740
7002	0.2166	1.1215	0.0654	4661	5016
6867	0.2297	1.1322	0.0761	4923	5352
6691	0.2437	1.1486	0.0925	5153	5703
6551	0.2551	1.1617	0.1056	5335	5987
6404	0.2693	1.1755	0.1194	5574	6340
6217	0.2827	1.1916	0.1355	5761	6666
6088	0.2932	1.2040	0.1479	5903	6920
5859	0.3083	1.2241	0.1680	6069	7277
5672	0.3201	1.2388	0.1827	6200	7553
5537	0.3313	1.2527	0.1966	6317	7812
5426	0.3462	1.2684	0.2123	6494	8156
5320	0.3586	1.2801	0.2240	6653	8444
5203	0.3704	1.2922	0.2361	6784	8715
5016	0.3835	1.3109	0.2548	6853	9005
4869	0.3960	1.3255	0.2694	6952	9283
4676	0.4106	1.3472	0.2911	6991	9595
4518	0.4241	1.3611	0.3050	7103	9889
4406	0.4333	1.3701	0.3140	7182	10088
4236	0.4487	1.3981	0.3420	7101	10392
4137	0.4590	1.4025	0.3464	7265	10618
3955	0.4746	1.4266	0.3705	7225	10925
3873	0.4844	1.4391	0.3830	7239	11125
3744	0.4966	1.4536	0.3975	7265	11372
3609	0.5132	1.4745	0.4184	7267	11698
3486	0.5249	1.4890	0.4329	7267	11929
3363	0.5366	1.5025	0.4464	7276	12160
3199	0.5542	1.5213	0.4652	7298	12498

Table A.5a J-resistance test data for Compact Specimen A53W1-FL-5
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J _D , kJ/m ²	J _M , kJ/m ²
0.000	0.000	26.634	0.000	0.0	0.0
24.996	0.594	26.634	0.000	40.5	40.5
28.503	1.161	26.634	0.000	122.1	122.1
30.348	1.768	26.634	0.000	218.2	218.2
31.535	2.337	26.634	0.000	313.0	313.0
32.484	2.926	26.634	0.000	414.5	414.5
33.275	3.510	26.634	0.000	517.9	517.9
33.803	4.079	26.634	0.000	620.6	620.6
34.198	4.681	26.634	0.000	730.8	730.8
34.620	5.258	26.634	0.000	837.6	837.6
34.857	5.855	26.634	0.000	949.2	949.2
35.121	6.449	26.634	0.000	1061.2	1061.2
35.306	6.995	26.634	0.000	1164.7	1164.7
35.490	7.577	26.634	0.000	1275.5	1275.5
35.649	8.131	26.634	0.000	1381.5	1381.5
35.226	8.700	26.634	0.000	1490.1	1490.1
34.435	8.992	26.883	0.249	1523.3	1543.9
33.829	9.197	27.157	0.523	1537.1	1581.0
32.985	9.413	27.460	0.825	1549.3	1619.3
32.194	9.649	27.964	1.330	1545.2	1659.5
31.087	9.972	28.468	1.833	1555.5	1714.9
30.533	10.208	28.741	2.107	1571.5	1755.8
29.979	10.437	29.062	2.427	1580.6	1794.8
29.320	10.673	29.470	2.836	1581.4	1834.2
28.476	10.914	29.748	3.113	1595.5	1875.0
27.712	11.143	30.127	3.492	1595.8	1912.3
26.973	11.397	30.534	3.900	1596.3	1953.2
26.288	11.547	30.777	4.143	1596.0	1977.3
25.392	11.796	31.170	4.535	1595.1	2016.3
24.944	12.042	31.605	4.971	1588.0	2054.1
24.363	12.291	31.926	5.292	1593.5	2093.2
23.810	12.576	32.360	5.725	1591.0	2136.7
23.493	12.713	32.673	6.038	1578.0	2157.2
22.992	13.010	33.091	6.457	1578.2	2202.9
22.518	13.282	33.386	6.751	1588.1	2245.4
22.307	13.419	33.695	7.060	1573.9	2265.7
21.647	13.706	34.165	7.530	1563.9	2308.7
21.067	14.003	34.579	7.944	1561.4	2353.7
20.804	14.150	34.782	8.147	1560.4	2376.3
20.277	14.448	35.197	8.562	1556.2	2420.8
19.934	14.597	35.543	8.908	1536.4	2442.2
19.301	14.907	36.081	9.446	1516.4	2486.8
18.932	15.083	36.413	9.778	1501.6	2512.2
18.404	15.403	36.883	10.249	1490.8	2559.2
18.035	15.578	37.174	10.540	1480.3	2584.9
17.191	15.926	37.705	11.070	1463.1	2634.5
16.902	16.111	38.090	11.456	1439.2	2659.8
16.691	16.284	38.403	11.768	1423.6	2684.3
16.400	16.457	38.666	12.032	1414.8	2709.6

Table A.5b J-resistance test data for Compact Specimen A53W1-FL-5
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J _D , $\frac{\text{inch-lb}}{\text{inch}^2}$	J _M , $\frac{\text{inch-lb}}{\text{inch}^2}$
0	0.0000	1.0486	0.0000	0	0
5555	0.0234	1.0486	0.0000	231	231
6334	0.0457	1.0486	0.0000	697	697
6744	0.0696	1.0486	0.0000	1246	1246
7008	0.0920	1.0486	0.0000	1787	1787
7219	0.1152	1.0486	0.0000	2367	2367
7395	0.1382	1.0486	0.0000	2957	2957
7512	0.1606	1.0486	0.0000	3544	3544
7600	0.1843	1.0486	0.0000	4173	4173
7693	0.2070	1.0486	0.0000	4783	4783
7746	0.2305	1.0486	0.0000	5420	5420
7805	0.2539	1.0486	0.0000	6059	6059
7846	0.2754	1.0486	0.0000	6650	6650
7887	0.2983	1.0486	0.0000	7283	7283
7922	0.3201	1.0486	0.0000	7889	7889
7828	0.3425	1.0486	0.0000	8508	8508
7652	0.3540	1.0584	0.0098	8698	8816
7518	0.3621	1.0692	0.0206	8777	9027
7330	0.3706	1.0811	0.0325	8846	9246
7154	0.3799	1.1009	0.0523	8823	9476
6908	0.3926	1.1208	0.0722	8882	9792
6785	0.4019	1.1315	0.0829	8973	10025
6662	0.4109	1.1442	0.0956	9025	10248
6516	0.4202	1.1602	0.1116	9030	10473
6328	0.4297	1.1712	0.1226	9110	10706
6158	0.4387	1.1861	0.1375	9112	10919
5994	0.4487	1.2021	0.1535	9115	11153
5842	0.4546	1.2117	0.1631	9113	11290
5643	0.4644	1.2272	0.1786	9108	11513
5543	0.4741	1.2443	0.1957	9067	11729
5414	0.4839	1.2569	0.2083	9099	11952
5291	0.4951	1.2740	0.2254	9085	12201
5221	0.5005	1.2863	0.2377	9010	12318
5109	0.5122	1.3028	0.2542	9012	12578
5004	0.5229	1.3144	0.2658	9068	12821
4957	0.5283	1.3266	0.2780	8987	12937
4811	0.5396	1.3451	0.2965	8930	13183
4682	0.5513	1.3614	0.3128	8916	13440
4623	0.5571	1.3694	0.3208	8910	13569
4506	0.5688	1.3857	0.3371	8886	13823
4430	0.5747	1.3993	0.3507	8773	13945
4289	0.5869	1.4205	0.3719	8659	14200
4207	0.5938	1.4336	0.3850	8574	14345
4090	0.6064	1.4521	0.4035	8512	14613
4008	0.6133	1.4636	0.4150	8453	14760
3820	0.6270	1.4844	0.4358	8354	15043
3756	0.6343	1.4996	0.4510	8218	15188
3709	0.6411	1.5119	0.4633	8129	15327
3645	0.6479	1.5223	0.4737	8078	15472

Table A.6a Test data from C(T) Specimen A8W4-FL-1
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	J_D		J_{III} , kJ/m ²	$J_{tot}^{(b)}$, kJ/m ²	J_m , kJ/m ²
				$J_{nom}^{(a)}$, kJ/m ²	J_I , kJ/m ²			
0.00	0.00	26.04	0.00	0.0	0.0	0.0	0.0	0.0
15.56	0.26	26.04	0.00	10.3	5.7	2.8	8.4	10.3
24.01	0.52	26.04	0.00	36.5	20.1	9.8	29.9	36.5
29.10	0.82	26.04	0.00	76.5	42.1	20.6	62.7	76.5
30.74	1.03	26.04	0.00	108.4	59.6	29.2	88.8	108.4
32.06	1.30	26.04	0.00	151.8	83.5	40.8	124.3	151.8
32.91	1.56	26.04	0.00	194.6	107.0	52.3	159.4	194.6
33.63	1.80	26.04	0.00	234.2	128.8	63.0	191.8	234.2
34.34	2.10	26.04	0.00	285.4	157.0	76.8	233.7	285.4
34.79	2.29	26.04	0.00	320.1	176.1	86.1	262.2	320.1
35.55	2.67	26.04	0.00	386.3	212.5	103.9	316.4	386.3
35.88	2.84	26.04	0.00	417.7	229.7	112.4	342.1	417.7
36.40	3.11	26.04	0.00	467.5	257.1	125.8	382.9	467.5
36.74	3.32	26.04	0.00	506.5	278.6	136.2	414.8	506.5
37.16	3.62	26.04	0.00	562.2	309.2	151.2	460.4	562.2
37.43	3.82	26.04	0.00	599.6	329.8	161.3	491.1	599.6
37.43	3.82	26.04	0.00	599.6	329.8	161.3	491.1	599.6
37.54	3.91	26.08	0.05	614.5	338.0	165.3	503.3	615.9
37.79	4.12	26.19	0.15	651.0	358.0	175.1	533.2	655.8
38.07	4.45	26.34	0.30	709.7	390.3	190.9	581.2	719.9
38.05	4.64	26.43	0.39	742.2	408.2	199.7	607.9	755.8
37.96	4.91	26.55	0.51	790.2	434.6	212.6	647.2	808.6
37.80	5.17	26.69	0.65	834.3	458.9	224.4	683.3	859.0
37.54	5.39	26.84	0.80	870.7	478.9	234.2	713.1	902.0
37.17	5.66	27.02	0.99	911.8	501.5	245.3	746.8	952.1
36.53	5.99	27.32	1.28	960.3	528.2	258.3	786.5	1015.7
35.86	6.20	27.58	1.54	985.9	542.2	265.2	807.5	1055.1
34.82	6.42	27.94	1.90	1006.8	553.7	270.8	824.6	1095.9
33.56	6.68	28.41	2.37	1026.2	564.4	276.0	840.5	1142.2
32.72	6.95	28.82	2.78	1047.5	576.1	281.8	857.9	1188.2
32.08	7.19	29.19	3.16	1068.0	587.4	287.3	874.7	1231.8
31.24	7.48	29.60	3.56	1092.1	600.7	293.8	894.4	1281.6
29.97	7.76	30.11	4.08	1106.2	608.4	297.6	906.0	1329.8
28.64	7.97	30.56	4.52	1110.8	610.9	298.8	909.7	1364.4
26.74	8.28	31.28	5.24	1108.5	609.7	298.2	907.9	1412.3
25.90	8.47	31.74	5.71	1103.8	607.1	296.9	904.0	1440.6
24.91	8.81	32.57	6.53	1093.1	601.2	294.0	895.2	1489.5
24.36	9.02	33.07	7.04	1087.5	598.1	292.5	890.7	1521.1
23.77	9.25	33.55	7.52	1087.4	598.1	292.5	890.6	1557.0
23.16	9.54	34.01	7.98	1096.1	602.9	294.9	897.7	1601.1
22.73	9.77	34.35	8.31	1107.1	608.9	297.8	906.7	1638.0
22.09	10.07	34.74	8.71	1121.0	616.5	301.5	918.1	1684.3
21.59	10.27	35.02	8.99	1128.5	620.7	303.6	924.2	1715.0
20.99	10.53	35.36	9.33	1139.5	626.7	306.5	933.3	1755.0
20.49	10.80	35.72	9.68	1149.8	632.4	309.3	941.7	1796.5
20.03	11.04	36.03	10.00	1157.4	636.6	311.3	947.9	1832.2
19.53	11.30	36.37	10.33	1165.9	641.2	313.6	954.9	1871.4
18.91	11.67	36.77	10.73	1183.8	651.1	318.4	969.5	1927.4
18.60	11.84	36.93	10.90	1194.2	656.8	321.2	978.0	1953.9
18.19	12.07	37.14	11.10	1207.6	664.2	324.8	989.0	1987.7
17.79	12.29	37.34	11.30	1220.5	671.3	328.3	999.6	2021.2

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_I + J_{III}$.

Table A.6b Test data from C(T) Specimen A8W4-FL-1
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		$J_{tot}^{(b)}$		J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_I , lb/inch	J_{III} , lb/inch	$J_{tot}^{(b)}$, lb/inch	
0	0.0000	1.0251	0.0000	0	0	0	0	0
3458	0.0103	1.0251	0.0000	59	32	16	48	59
5335	0.0205	1.0251	0.0000	208	115	56	171	208
6466	0.0322	1.0251	0.0000	437	240	118	358	437
6832	0.0405	1.0251	0.0000	619	341	167	507	619
7124	0.0513	1.0251	0.0000	867	477	233	710	867
7313	0.0615	1.0251	0.0000	1111	612	299	911	1111
7474	0.0708	1.0251	0.0000	1337	736	360	1096	1337
7631	0.0825	1.0251	0.0000	1630	897	439	1336	1630
7732	0.0903	1.0251	0.0000	1828	1006	492	1498	1828
7900	0.1050	1.0251	0.0000	2206	1214	594	1808	2206
7974	0.1118	1.0251	0.0000	2385	1313	642	1955	2385
8089	0.1226	1.0251	0.0000	2670	1469	719	2188	2670
8164	0.1309	1.0251	0.0000	2892	1592	779	2370	2892
8258	0.1426	1.0251	0.0000	3210	1767	864	2631	3210
8317	0.1504	1.0251	0.0000	3424	1884	922	2806	3424
8317	0.1504	1.0251	0.0000	3424	1884	922	2806	3424
8342	0.1538	1.0269	0.0018	3509	1931	945	2876	3517
8397	0.1621	1.0310	0.0059	3717	2046	1001	3047	3745
8459	0.1753	1.0370	0.0119	4052	2230	1091	3321	4111
8456	0.1826	1.0406	0.0155	4238	2333	1141	3473	4316
8435	0.1934	1.0452	0.0201	4512	2483	1215	3698	4617
8401	0.2036	1.0509	0.0258	4764	2622	1282	3905	4905
8343	0.2124	1.0566	0.0315	4972	2736	1338	4075	5151
8260	0.2227	1.0640	0.0389	5206	2866	1402	4267	5436
8118	0.2358	1.0756	0.0505	5483	3018	1476	4494	5799
7969	0.2441	1.0858	0.0607	5629	3099	1515	4614	6025
7738	0.2529	1.0999	0.0748	5749	3164	1548	4712	6258
7458	0.2632	1.1183	0.0932	5859	3225	1577	4803	6522
7270	0.2734	1.1347	0.1096	5981	3292	1610	4902	6785
7129	0.2832	1.1494	0.1243	6098	3357	1642	4998	7033
6943	0.2944	1.1653	0.1402	6236	3432	1679	5111	7318
6661	0.3057	1.1856	0.1605	6316	3477	1700	5177	7593
6365	0.3140	1.2030	0.1779	6343	3491	1707	5199	7791
5943	0.3262	1.2314	0.2063	6330	3484	1704	5188	8064
5755	0.3335	1.2497	0.2246	6303	3469	1697	5166	8226
5535	0.3467	1.2822	0.2571	6241	3435	1680	5116	8505
5413	0.3550	1.3021	0.2770	6210	3418	1672	5089	8686
5282	0.3643	1.3210	0.2959	6209	3418	1671	5089	8890
5148	0.3755	1.3392	0.3141	6259	3445	1685	5130	9142
5051	0.3848	1.3522	0.3271	6321	3479	1702	5181	9353
4908	0.3965	1.3679	0.3428	6401	3523	1723	5246	9617
4797	0.4043	1.3789	0.3538	6444	3547	1735	5281	9793
4664	0.4146	1.3923	0.3672	6507	3581	1752	5333	10021
4553	0.4253	1.4063	0.3812	6566	3614	1767	5381	10258
4452	0.4346	1.4187	0.3936	6609	3638	1779	5417	10462
4341	0.4448	1.4318	0.4067	6657	3664	1792	5456	10686
4202	0.4595	1.4476	0.4225	6760	3721	1820	5540	11005
4133	0.4663	1.4541	0.4290	6819	3753	1836	5589	11157
4042	0.4751	1.4621	0.4370	6895	3795	1856	5652	11350
3953	0.4839	1.4701	0.4450	6969	3836	1876	5712	11541

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_I + J_{III}$.

Table A.7a Test data from C(T) Specimen A8W4-FL-2
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	J_D		$J_{tot}^{(b)}$		J_m kJ/m ²
				$J_{nom}^{(a)}$ kJ/m ²	J_i kJ/m ²	J_{iii} kJ/m ²	$J_{tot}^{(b)}$ kJ/m ²	
0.00	0.00	26.03	0.00	0.0	0.0	0.0	0.0	0.0
22.91	0.37	26.03	0.00	21.7	11.9	5.8	17.8	21.7
28.32	0.74	26.03	0.00	70.0	38.5	18.8	57.3	70.0
30.14	1.11	26.03	0.00	125.4	69.0	33.7	102.7	125.4
31.46	1.51	26.03	0.00	186.9	102.8	50.3	153.1	186.9
32.35	1.82	26.03	0.00	238.3	131.1	64.1	195.2	238.3
33.17	2.20	26.03	0.00	301.2	165.7	81.0	246.7	301.2
34.07	2.61	26.03	0.00	370.9	204.0	99.8	303.8	370.9
34.75	2.98	26.03	0.00	434.8	239.1	117.0	356.1	434.8
35.36	3.30	26.03	0.00	492.2	270.7	132.4	403.1	492.2
35.91	3.65	26.03	0.00	556.0	305.8	149.6	455.4	556.0
36.60	4.07	26.03	0.00	632.6	347.9	170.2	518.1	632.6
37.18	4.44	26.03	0.00	702.0	386.1	188.8	574.9	702.0
37.57	4.77	26.03	0.00	764.1	420.3	205.5	625.8	764.1
37.92	5.13	26.03	0.00	833.2	458.3	224.1	682.4	833.2
38.05	5.47	26.03	0.00	898.8	494.3	241.8	736.1	898.8
37.99	5.56	26.07	0.04	914.0	502.7	245.9	748.6	915.8
37.92	5.74	26.18	0.15	942.2	518.2	253.5	771.7	949.7
37.36	5.92	26.36	0.33	968.6	532.7	260.6	793.3	985.2
36.89	6.11	26.55	0.51	993.7	546.5	267.3	813.8	1019.9
36.57	6.31	26.73	0.70	1020.7	561.4	274.6	836.0	1056.9
35.70	6.60	27.10	1.08	1053.0	579.2	283.3	862.4	1110.3
35.44	6.70	27.26	1.23	1062.1	584.2	285.7	869.9	1128.4
34.65	6.93	27.51	1.48	1088.8	598.8	292.9	891.7	1170.0
33.83	7.15	27.76	1.73	1113.2	612.3	299.5	911.7	1210.0
32.59	7.37	28.10	2.07	1129.2	621.1	303.8	924.8	1247.5
31.77	7.49	28.37	2.34	1132.0	622.6	304.5	927.1	1267.6
29.80	7.74	28.89	2.86	1138.6	626.2	306.3	932.5	1308.7
28.79	7.96	29.42	3.38	1138.3	626.1	306.2	932.3	1343.4
28.16	8.10	29.87	3.84	1128.9	620.9	303.7	924.6	1364.9
27.24	8.33	30.30	4.27	1133.6	623.5	304.9	928.4	1399.5
26.02	8.56	30.75	4.72	1136.6	625.1	305.7	930.9	1434.1
25.50	8.67	31.02	4.99	1134.3	623.9	305.1	929.0	1450.8
24.42	8.92	31.48	5.45	1138.2	626.0	306.2	932.2	1488.1
23.94	9.07	31.86	5.83	1131.0	622.0	304.2	926.3	1509.3
22.60	9.31	32.48	6.45	1117.5	614.6	300.6	915.2	1541.5
20.93	9.59	33.21	7.18	1098.7	604.3	295.6	899.8	1578.3
20.38	9.75	33.92	7.89	1063.3	584.8	286.0	870.8	1596.5
19.80	9.92	34.32	8.29	1053.8	579.6	283.5	863.1	1617.8
19.46	10.06	35.03	8.99	1016.0	558.8	273.3	832.1	1633.7
18.98	10.35	35.53	9.50	1016.0	558.8	273.3	832.1	1672.5
18.75	10.49	35.71	9.68	1022.2	562.2	275.0	837.2	1692.7
18.19	10.77	36.11	10.08	1029.0	566.0	276.8	842.8	1731.3
17.98	10.92	36.41	10.38	1024.0	563.2	275.5	838.7	1751.0
17.80	11.06	36.57	10.54	1029.9	566.4	277.0	843.5	1770.4
17.35	11.35	36.96	10.93	1038.1	571.0	279.2	850.2	1811.5
17.19	11.50	37.25	11.22	1032.7	568.0	277.8	845.8	1830.5
16.85	11.66	37.42	11.39	1040.4	572.2	279.9	852.1	1853.6
16.48	11.82	37.73	11.70	1034.5	569.0	278.3	847.3	1874.8
16.22	11.97	37.89	11.86	1041.0	572.5	280.0	852.6	1896.0

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.7b Test data from C(T) Specimen A8W4-FL-2
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		$J_{tot}^{(b)}$		J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_i , lb/inch	J_{iii} , lb/inch	$J_{tot}^{(b)}$, lb/inch	
0	0.0000	1.0248	0.0000	0	0	0	0	0
5092	0.0145	1.0248	0.0000	124	68	33	102	124
6293	0.0291	1.0248	0.0000	400	220	108	328	400
6697	0.0438	1.0248	0.0000	716	394	193	587	716
6990	0.0593	1.0248	0.0000	1067	587	287	875	1067
7190	0.0718	1.0248	0.0000	1361	749	366	1115	1361
7371	0.0867	1.0248	0.0000	1720	947	463	1410	1720
7570	0.1028	1.0248	0.0000	2118	1166	570	1736	2118
7723	0.1172	1.0248	0.0000	2483	1367	668	2035	2483
7857	0.1299	1.0248	0.0000	2810	1547	757	2303	2810
7981	0.1438	1.0248	0.0000	3175	1747	855	2602	3175
8133	0.1602	1.0248	0.0000	3612	1988	972	2961	3612
8262	0.1748	1.0248	0.0000	4009	2206	1079	3285	4009
8350	0.1877	1.0248	0.0000	4363	2401	1175	3576	4363
8426	0.2019	1.0248	0.0000	4758	2619	1281	3899	4758
8455	0.2153	1.0248	0.0000	5132	2825	1382	4206	5132
8443	0.2188	1.0263	0.0015	5219	2873	1405	4278	5229
8426	0.2258	1.0308	0.0060	5380	2961	1448	4409	5423
8303	0.2332	1.0379	0.0131	5531	3044	1489	4533	5625
8197	0.2405	1.0451	0.0203	5674	3123	1527	4651	5823
8127	0.2483	1.0523	0.0275	5828	3208	1569	4777	6035
7934	0.2598	1.0671	0.0423	6013	3309	1619	4928	6340
7875	0.2637	1.0732	0.0484	6064	3338	1633	4971	6443
7699	0.2727	1.0830	0.0582	6217	3422	1674	5096	6681
7518	0.2815	1.0931	0.0683	6356	3499	1711	5210	6909
7242	0.2900	1.1064	0.0816	6448	3549	1736	5285	7123
7061	0.2947	1.1169	0.0921	6464	3558	1740	5298	7238
6621	0.3047	1.1376	0.1128	6501	3578	1750	5329	7472
6398	0.3135	1.1581	0.1333	6500	3578	1750	5327	7671
6258	0.3191	1.1759	0.1511	6446	3548	1735	5283	7793
6053	0.3279	1.1930	0.1682	6473	3563	1743	5305	7991
5783	0.3369	1.2107	0.1859	6490	3572	1747	5319	8189
5666	0.3413	1.2211	0.1963	6477	3565	1744	5309	8284
5426	0.3513	1.2392	0.2144	6499	3577	1750	5327	8497
5320	0.3572	1.2544	0.2296	6458	3555	1739	5293	8618
5022	0.3665	1.2786	0.2538	6381	3512	1718	5230	8802
4652	0.3777	1.3075	0.2827	6273	3453	1689	5142	9012
4529	0.3840	1.3353	0.3105	6072	3342	1634	4976	9116
4400	0.3904	1.3512	0.3264	6017	3312	1620	4932	9237
4324	0.3962	1.3789	0.3541	5802	3193	1562	4755	9328
4219	0.4075	1.3988	0.3740	5801	3193	1562	4755	9550
4166	0.4131	1.4059	0.3811	5837	3213	1571	4784	9665
4043	0.4241	1.4215	0.3967	5875	3234	1582	4816	9885
3996	0.4299	1.4334	0.4086	5847	3218	1574	4792	9998
3955	0.4353	1.4398	0.4150	5881	3237	1583	4820	10109
3856	0.4470	1.4552	0.4304	5928	3263	1596	4858	10343
3820	0.4526	1.4664	0.4416	5897	3246	1587	4833	10452
3744	0.4590	1.4733	0.4485	5941	3270	1599	4869	10584
3662	0.4653	1.4854	0.4606	5907	3251	1590	4841	10705
3604	0.4712	1.4918	0.4670	5944	3272	1600	4872	10826

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.8a Test data from C(T) Specimen A8W4-FL-3
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	J_D		$J_{tot}^{(b)}$, kJ/m ²	J_m , kJ/m ²
				$J_{nom}^{(a)}$, kJ/m ²	J_i , kJ/m ²		
0.00	0.00	26.74	0.00	0.0	0.0	0.0	0.0
21.67	0.32	26.74	0.00	18.9	10.4	5.1	18.9
28.21	0.65	26.74	0.00	61.4	33.8	16.5	61.4
30.35	0.97	26.74	0.00	110.9	61.0	29.8	110.9
31.69	1.31	26.74	0.00	165.4	91.0	44.5	165.4
32.51	1.59	26.74	0.00	212.4	116.8	57.1	212.4
33.28	1.88	26.74	0.00	262.7	144.5	70.7	262.7
34.09	2.22	26.74	0.00	323.7	178.0	87.1	323.7
34.70	2.53	26.74	0.00	378.6	208.2	101.8	378.6
35.17	2.82	26.74	0.00	432.0	237.6	116.2	432.0
35.62	3.14	26.74	0.00	490.4	269.7	131.9	490.4
35.99	3.46	26.74	0.00	550.9	303.0	148.2	550.9
36.31	3.79	26.74	0.00	613.5	337.4	165.0	613.5
36.57	4.11	26.74	0.00	673.6	370.5	181.2	673.6
36.78	4.44	26.74	0.00	738.0	405.9	198.5	738.0
36.70	4.69	26.74	0.00	785.9	432.2	211.4	785.9
36.26	4.78	26.74	0.00	803.4	441.9	216.1	803.4
35.15	4.94	26.99	0.25	822.2	452.2	221.2	832.9
34.41	5.13	27.22	0.47	845.3	464.9	227.4	866.3
31.85	5.31	27.66	0.91	854.9	470.2	230.0	896.5
30.77	5.48	28.02	1.27	864.8	475.6	232.6	923.7
29.66	5.69	28.55	1.80	872.7	480.0	234.8	957.6
29.32	5.79	28.80	2.06	875.2	481.4	235.4	973.1
28.77	5.98	29.11	2.36	889.6	489.3	239.3	1003.1
28.16	6.18	29.44	2.70	903.1	496.7	242.9	1034.3
27.92	6.28	29.61	2.86	909.9	500.4	244.8	1049.9
27.32	6.47	29.95	3.21	921.8	507.0	248.0	1080.8
26.76	6.67	30.27	3.52	934.1	513.8	251.3	1110.7
26.52	6.77	30.42	3.67	941.9	518.0	253.4	1127.0
25.58	6.98	30.74	4.00	954.9	525.2	256.9	1159.2
24.97	7.09	30.98	4.23	956.8	526.2	257.4	1175.0
23.94	7.30	31.48	4.74	956.8	526.2	257.4	1205.7
22.73	7.52	32.03	5.28	952.9	524.1	256.3	1235.4
22.28	7.63	32.35	5.60	947.9	521.3	255.0	1250.6
21.86	7.74	32.72	5.98	938.4	516.1	252.4	1264.6
21.07	7.95	33.35	6.60	926.8	509.7	249.3	1292.6
20.17	8.18	33.91	7.16	919.7	505.8	247.4	1321.9
19.57	8.29	34.20	7.45	915.4	503.5	246.2	1336.6
18.93	8.40	34.53	7.79	907.4	499.1	244.1	1350.8
18.11	8.66	35.15	8.40	897.9	493.8	241.5	1382.3
17.72	8.80	35.37	8.63	901.5	495.8	242.5	1401.0
17.43	8.92	35.58	8.83	902.8	496.5	242.9	1416.5
17.06	9.05	35.91	9.17	896.1	492.9	241.1	1433.1
16.30	9.33	36.26	9.51	906.8	498.7	243.9	1468.4
16.03	9.46	36.59	9.84	899.4	494.7	241.9	1484.8
15.66	9.60	36.78	10.03	902.6	496.4	242.8	1501.9
15.11	9.73	37.02	10.28	900.5	495.3	242.2	1518.0
14.13	10.12	37.70	10.96	893.0	491.1	240.2	1562.3

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.8b Test data from C(T) Specimen A8W4-FL-3
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		$J_{tot}^{(b)}$		J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_i , lb/inch	J_{iii} , lb/inch	$J_{tot}^{(b)}$, lb/inch	
0	0.0000	1.0529	0.0000	0	0	0	0	0
4816	0.0128	1.0529	0.0000	108	59	29	88	108
6270	0.0256	1.0529	0.0000	351	193	94	287	351
6744	0.0383	1.0529	0.0000	633	349	170	519	633
7043	0.0515	1.0529	0.0000	944	520	254	774	944
7225	0.0625	1.0529	0.0000	1213	668	326	994	1213
7395	0.0740	1.0529	0.0000	1500	826	404	1229	1500
7576	0.0876	1.0529	0.0000	1848	1017	498	1515	1848
7711	0.0996	1.0529	0.0000	2162	1190	582	1772	2162
7816	0.1111	1.0529	0.0000	2467	1358	664	2022	2467
7916	0.1235	1.0529	0.0000	2800	1541	754	2295	2800
7998	0.1362	1.0529	0.0000	3146	1731	847	2578	3146
8068	0.1492	1.0529	0.0000	3503	1928	943	2871	3503
8127	0.1616	1.0529	0.0000	3846	2117	1035	3152	3846
8174	0.1748	1.0529	0.0000	4214	2319	1134	3454	4214
8156	0.1846	1.0529	0.0000	4488	2470	1208	3678	4488
8057	0.1882	1.0529	0.0000	4587	2525	1235	3760	4587
7811	0.1946	1.0626	0.0097	4694	2584	1264	3848	4756
7647	0.2019	1.0715	0.0186	4827	2657	1299	3956	4946
7078	0.2090	1.0888	0.0359	4882	2687	1314	4001	5119
6838	0.2156	1.1030	0.0501	4938	2718	1329	4047	5274
6592	0.2241	1.1238	0.0709	4983	2743	1341	4084	5468
6516	0.2280	1.1340	0.0811	4997	2751	1345	4096	5557
6393	0.2354	1.1459	0.0930	5080	2796	1367	4163	5728
6258	0.2432	1.1592	0.1063	5157	2838	1388	4227	5906
6205	0.2471	1.1656	0.1127	5196	2860	1399	4258	5995
6070	0.2549	1.1793	0.1264	5264	2897	1417	4314	6171
5947	0.2625	1.1916	0.1387	5334	2936	1436	4372	6342
5895	0.2666	1.1975	0.1446	5378	2960	1448	4408	6435
5684	0.2749	1.2103	0.1574	5453	3001	1468	4469	6619
5549	0.2791	1.2195	0.1666	5464	3007	1471	4478	6709
5320	0.2876	1.2395	0.1866	5463	3007	1471	4478	6885
5051	0.2961	1.2608	0.2079	5441	2995	1465	4460	7054
4951	0.3005	1.2735	0.2206	5413	2979	1457	4436	7141
4857	0.3047	1.2882	0.2353	5358	2949	1442	4392	7221
4682	0.3132	1.3128	0.2599	5292	2913	1425	4337	7381
4482	0.3220	1.3350	0.2821	5251	2890	1414	4304	7548
4348	0.3264	1.3464	0.2935	5227	2877	1407	4284	7632
4207	0.3308	1.3596	0.3067	5181	2852	1395	4247	7713
4025	0.3408	1.3838	0.3309	5127	2822	1380	4202	7893
3938	0.3464	1.3926	0.3397	5147	2833	1386	4219	8000
3873	0.3511	1.4007	0.3478	5155	2837	1388	4225	8088
3791	0.3564	1.4138	0.3609	5117	2816	1377	4194	8183
3621	0.3672	1.4275	0.3746	5178	2850	1394	4244	8384
3563	0.3726	1.4404	0.3875	5136	2827	1383	4209	8478
3481	0.3779	1.4479	0.3950	5154	2837	1387	4224	8576
3357	0.3831	1.4575	0.4046	5142	2830	1384	4214	8668
3141	0.3984	1.4843	0.4314	5099	2807	1373	4179	8921

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.9a Test data from C(T) Specimen A8W4-FL-5
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	J_D		J_{III} , kJ/m ²	$J_{tot}^{(b)}$, kJ/m ²	J_m , kJ/m ²
				$J_{nom}^{(a)}$, kJ/m ²	J_I , kJ/m ²			
0.00	0.00	25.84	0.00	0.0	0.0	0.0	0.0	0.0
21.96	0.29	25.84	0.00	16.6	9.1	4.5	13.6	16.6
29.87	0.58	25.84	0.00	54.7	30.1	14.7	44.8	54.7
32.72	0.86	25.84	0.00	98.6	54.2	26.5	80.8	98.6
34.17	1.15	25.84	0.00	147.2	81.0	39.6	120.6	147.2
35.41	1.45	25.84	0.00	200.4	110.2	53.9	164.1	200.4
36.44	1.74	25.84	0.00	252.6	138.9	67.9	206.9	252.6
37.34	2.03	25.84	0.00	306.7	168.7	82.5	251.2	306.7
38.10	2.30	25.84	0.00	359.0	197.4	96.6	294.0	359.0
38.65	2.59	25.84	0.00	415.8	228.7	111.9	340.5	415.8
39.21	2.88	25.84	0.00	471.8	259.5	126.9	386.4	471.8
39.71	3.17	25.84	0.00	530.1	291.6	142.6	434.2	530.1
40.21	3.50	25.84	0.00	596.4	328.0	160.4	488.5	596.4
40.58	3.76	25.84	0.00	649.4	357.2	174.7	531.9	649.4
40.90	4.03	25.84	0.00	705.9	388.2	189.9	578.1	705.9
41.05	4.30	25.84	0.00	762.3	419.3	205.1	624.3	762.3
41.00	4.41	25.89	0.06	782.0	430.1	210.4	640.5	784.2
40.69	4.62	26.06	0.23	817.8	449.8	220.0	669.8	827.2
40.53	4.81	26.20	0.36	851.5	468.3	229.1	697.4	866.7
40.42	5.00	26.31	0.48	884.3	486.4	237.9	724.2	904.7
40.10	5.19	26.49	0.65	914.8	503.1	246.1	749.2	943.5
39.95	5.39	26.67	0.84	946.3	520.5	254.6	775.0	984.3
39.81	5.59	26.82	0.98	979.6	538.8	263.5	802.3	1025.0
39.71	5.73	26.89	1.06	1005.0	552.7	270.3	823.1	1054.3
39.13	5.96	27.14	1.31	1037.5	570.6	279.1	849.7	1100.6
34.36	6.18	29.19	3.35	947.2	521.0	254.8	775.8	1124.4
33.25	6.36	29.49	3.65	962.7	529.5	259.0	788.5	1156.6
32.22	6.52	30.00	4.16	962.4	529.3	258.9	788.2	1184.9
31.01	6.77	30.46	4.62	979.7	538.8	263.5	802.4	1229.4
30.16	6.93	30.90	5.07	981.5	539.8	264.0	803.8	1257.8
29.14	7.09	31.19	5.35	991.5	545.3	266.7	812.0	1285.4
28.19	7.34	31.87	6.03	988.7	543.8	266.0	809.7	1325.4
27.66	7.52	32.35	6.51	989.0	544.0	266.0	810.0	1356.1
27.05	7.71	32.65	6.81	1002.0	551.1	269.5	820.6	1388.6
26.39	7.89	32.86	7.02	1020.2	561.1	274.4	835.5	1421.0
25.79	8.07	33.15	7.31	1029.2	566.1	276.9	842.9	1450.1
25.29	8.27	33.47	7.63	1039.4	571.7	279.6	851.3	1483.1
24.65	8.47	33.77	7.93	1051.2	578.2	282.8	860.9	1516.6
24.13	8.66	34.04	8.21	1062.5	584.4	285.8	870.2	1548.2
23.20	8.87	34.42	8.58	1067.8	587.3	287.2	874.5	1582.0
22.70	8.98	34.63	8.79	1069.1	588.0	287.6	875.6	1599.8
21.91	9.19	35.04	9.20	1069.8	588.4	287.8	876.2	1632.3
21.44	9.39	35.34	9.50	1076.5	592.1	289.6	881.7	1663.2
20.51	9.61	35.69	9.86	1080.6	594.3	290.7	885.0	1696.6
19.96	9.82	36.05	10.21	1082.6	595.4	291.2	886.6	1728.1
19.49	10.05	36.44	10.60	1082.7	595.5	291.2	886.7	1761.8
19.25	10.15	36.62	10.78	1083.2	595.8	291.4	887.1	1777.8
18.77	10.36	36.94	11.10	1086.4	597.5	292.2	889.8	1809.2
18.19	10.60	37.25	11.42	1093.6	601.5	294.2	895.7	1845.3

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_I + J_{III}$.

Table A.9b Test data from C(T) Specimen A8W4-FL-5
(Slant-notch with angle of 55 degrees from specimen face to follow fusion-line, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		J_{iii} , lb/inch	$J_{tot}^{(b)}$, lb/inch	J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_i , lb/inch			
0	0.0000	1.0172	0.0000	0	0	0	0	0
4881	0.0116	1.0172	0.0000	95	52	26	78	95
6639	0.0230	1.0172	0.0000	312	172	84	256	312
7272	0.0339	1.0172	0.0000	563	310	152	461	563
7594	0.0452	1.0172	0.0000	841	463	226	689	841
7869	0.0571	1.0172	0.0000	1144	630	308	938	1144
8098	0.0684	1.0172	0.0000	1442	794	388	1182	1442
8297	0.0798	1.0172	0.0000	1751	964	471	1435	1751
8467	0.0906	1.0172	0.0000	2050	1128	552	1680	2050
8590	0.1021	1.0172	0.0000	2374	1307	639	1946	2374
8713	0.1133	1.0172	0.0000	2694	1483	725	2208	2694
8824	0.1248	1.0172	0.0000	3027	1666	815	2481	3027
8936	0.1377	1.0172	0.0000	3405	1874	917	2791	3405
9018	0.1479	1.0172	0.0000	3708	2041	998	3039	3708
9088	0.1587	1.0172	0.0000	4031	2219	1085	3304	4031
9123	0.1694	1.0172	0.0000	4352	2396	1172	3568	4352
9111	0.1736	1.0194	0.0022	4465	2458	1202	3660	4478
9041	0.1819	1.0262	0.0090	4670	2570	1257	3827	4723
9006	0.1895	1.0314	0.0142	4862	2676	1309	3985	4949
8982	0.1968	1.0360	0.0188	5049	2779	1359	4139	5166
8912	0.2043	1.0428	0.0256	5223	2875	1406	4281	5387
8877	0.2122	1.0502	0.0330	5404	2974	1455	4429	5621
8848	0.2200	1.0558	0.0386	5593	3079	1506	4585	5853
8824	0.2256	1.0588	0.0416	5738	3159	1545	4703	6020
8695	0.2346	1.0686	0.0514	5924	3261	1595	4855	6285
7635	0.2434	1.1493	0.1321	5409	2977	1456	4433	6420
7389	0.2502	1.1611	0.1439	5497	3026	1480	4505	6604
7160	0.2566	1.1809	0.1637	5495	3025	1479	4504	6766
6891	0.2664	1.1992	0.1820	5594	3079	1506	4585	7020
6703	0.2729	1.2166	0.1994	5604	3085	1509	4593	7182
6475	0.2791	1.2279	0.2107	5662	3116	1524	4640	7339
6264	0.2888	1.2548	0.2376	5646	3107	1520	4627	7568
6147	0.2961	1.2735	0.2563	5647	3108	1520	4629	7743
6012	0.3035	1.2852	0.2680	5721	3149	1540	4689	7929
5865	0.3108	1.2935	0.2763	5825	3206	1568	4775	8114
5731	0.3176	1.3050	0.2878	5877	3235	1582	4817	8280
5619	0.3254	1.3177	0.3005	5935	3267	1598	4864	8469
5479	0.3333	1.3295	0.3123	6003	3304	1616	4920	8660
5361	0.3408	1.3403	0.3231	6067	3339	1633	4972	8840
5156	0.3491	1.3551	0.3379	6097	3356	1641	4997	9033
5045	0.3535	1.3634	0.3462	6105	3360	1643	5003	9135
4869	0.3618	1.3794	0.3622	6108	3362	1644	5007	9320
4764	0.3696	1.3913	0.3741	6147	3383	1655	5038	9497
4559	0.3782	1.4053	0.3881	6170	3396	1661	5057	9688
4436	0.3865	1.4191	0.4019	6182	3402	1664	5067	9868
4330	0.3955	1.4346	0.4174	6182	3403	1664	5067	10060
4277	0.3997	1.4416	0.4244	6185	3404	1665	5069	10151
4172	0.4080	1.4542	0.4370	6203	3414	1670	5084	10331
4043	0.4175	1.4667	0.4495	6245	3437	1681	5118	10536

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.10a J-resistance test data for Compact Specimen F33-4-SS-1
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J, kJ/m ²	J _M , kJ/m ²
4.72	0.01	28.77	0.00	0.1	0.1
6.25	0.10	28.77	0.00	2.0	2.0
12.46	0.43	28.77	0.00	13.9	13.9
18.62	0.94	28.77	0.00	44.9	44.9
24.82	3.41	28.77	0.00	252.9	252.9
31.01	6.67	28.77	0.00	606.3	606.3
37.22	11.10	28.77	0.00	1192.1	1192.1
43.34	17.52	28.77	0.00	2197.7	2197.7
43.37	17.56	28.77	0.00	2204.1	2204.1
43.48	17.73	28.83	0.06	2225.7	2233.0
43.61	17.94	28.92	0.15	2249.1	2268.4
43.71	18.31	29.05	0.28	2292.3	2329.5
43.83	19.24	29.38	0.61	2404.9	2488.0
43.96	19.88	29.61	0.84	2481.9	2599.8
43.91	20.65	29.91	1.14	2570.8	2734.5
43.80	20.76	29.96	1.19	2582.9	2754.2
43.69	20.87	30.01	1.24	2595.0	2774.0
43.58	21.10	30.10	1.33	2619.0	2813.5
43.33	21.65	30.36	1.59	2675.1	2911.5
43.18	21.99	30.52	1.75	2706.9	2970.9
43.08	22.21	30.64	1.87	2727.7	3010.7
42.92	22.56	30.81	2.04	2759.0	3072.7
42.81	22.80	30.94	2.16	2779.9	3115.0
42.71	23.02	31.06	2.28	2798.9	3155.1
42.42	23.60	31.38	2.61	2844.4	3259.1
42.29	23.79	31.49	2.71	2858.1	3292.7
42.15	23.95	31.58	2.81	2870.6	3322.2
42.06	24.06	31.64	2.87	2878.9	3342.5
41.75	24.39	31.83	3.06	2904.2	3402.8
41.63	24.51	31.89	3.12	2912.7	3423.2
41.53	24.61	31.94	3.17	2920.5	3441.7
41.41	24.73	32.01	3.24	2929.7	3463.9
41.27	24.87	32.08	3.31	2940.2	3488.9
41.15	24.99	32.15	3.38	2949.7	3511.6
40.75	25.39	32.37	3.60	2979.2	3583.4
40.09	26.03	32.71	3.93	3026.8	3700.1
39.44	26.67	33.03	4.26	3074.1	3814.7
38.79	27.31	33.34	4.57	3120.4	3929.2

Table A.10b J-resistance test data for Compact Specimen F33-4-SS-1
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J, <u>inch-lb</u> inch ²	J _M , <u>inch-lb</u> inch ²
1048	0.0005	1.1327	0.0000	1	1
1388	0.0040	1.1327	0.0000	11	11
2768	0.0169	1.1327	0.0000	79	79
4137	0.0372	1.1327	0.0000	256	256
5516	0.1343	1.1327	0.0000	1444	1444
6891	0.2627	1.1327	0.0000	3462	3462
8270	0.4368	1.1327	0.0000	6807	6807
9632	0.6899	1.1327	0.0000	12549	12549
9638	0.6914	1.1327	0.0000	12585	12585
9663	0.6982	1.1349	0.0022	12709	12751
9692	0.7065	1.1385	0.0058	12842	12953
9713	0.7207	1.1437	0.0110	13089	13301
9741	0.7573	1.1566	0.0239	13732	14207
9768	0.7827	1.1659	0.0332	14172	14845
9758	0.8130	1.1776	0.0449	14679	15614
9733	0.8174	1.1795	0.0468	14749	15727
9708	0.8218	1.1814	0.0487	14818	15839
9686	0.8306	1.1852	0.0525	14955	16065
9630	0.8525	1.1953	0.0626	15275	16625
9596	0.8657	1.2018	0.0691	15456	16964
9573	0.8745	1.2062	0.0735	15575	17191
9538	0.8882	1.2131	0.0804	15754	17545
9514	0.8975	1.2179	0.0852	15873	17787
9491	0.9063	1.2226	0.0899	15982	18016
9427	0.9292	1.2353	0.1026	16241	18610
9398	0.9365	1.2396	0.1069	16320	18801
9367	0.9429	1.2432	0.1105	16391	18970
9347	0.9473	1.2457	0.1130	16439	19086
9277	0.9604	1.2530	0.1203	16583	19430
9252	0.9648	1.2554	0.1227	16632	19546
9230	0.9688	1.2576	0.1249	16676	19652
9203	0.9736	1.2602	0.1275	16729	19779
9172	0.9790	1.2632	0.1305	16788	19921
9144	0.9839	1.2658	0.1331	16843	20051
9055	0.9995	1.2742	0.1415	17011	20461
8909	1.0250	1.2876	0.1549	17283	21128
8764	1.0500	1.3003	0.1676	17553	21782
8619	1.0750	1.3127	0.1800	17817	22436

Table A.11a J-resistance test data for Compact Specimen F33-4-SS-2
tested at 288 C (550 F); SI units

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Crack Extension, mm	J, kJ/m ²	J _M , kJ/m ²
0.89	0.04	28.53	0.0000	0.	0.
8.27	0.17	28.53	0.0000	2	2
13.05	0.25	28.53	0.0000	6	6
19.29	0.81	28.53	0.0000	40	40
25.33	3.01	28.53	0.0000	230	230
31.75	6.16	28.53	0.0000	578	578
38.00	10.33	28.53	0.0000	1140	1140
44.22	17.45	28.53	0.0000	2272	2272
44.38	18.00	28.79	0.2580	2330	2364
44.40	18.09	28.85	0.3140	2339	2381
44.48	19.52	29.42	0.8830	2502	2627
44.31	19.95	29.64	1.1100	2544	2703
44.15	20.41	29.93	1.3930	2580	2783
43.97	20.87	30.16	1.6210	2626	2865
43.77	21.30	30.38	1.8480	2664	2941
43.56	21.65	30.61	2.0740	2690	3005
43.37	21.86	30.72	2.1880	2709	3043
43.24	21.99	30.83	2.2990	2712	3065
42.99	22.21	30.95	2.4130	2733	3106
42.85	22.45	31.06	2.5270	2756	3149
42.67	22.68	31.18	2.6420	2779	3191
42.46	22.92	31.34	2.8090	2791	3234
42.35	23.02	31.40	2.8650	2799	3252
42.09	23.25	31.51	2.9790	2821	3295
41.96	23.36	31.57	3.0360	2831	3315
41.82	23.49	31.63	3.0940	2843	3338
41.55	23.73	31.74	3.2080	2864	3381
41.42	23.84	31.80	3.2650	2874	3401
40.22	24.89	32.47	3.9320	2930	3586
40.08	25.02	32.52	3.9890	2942	3609
39.95	25.13	32.58	4.0460	2951	3629
39.85	25.24	32.64	4.1020	2960	3649
39.54	25.65	32.86	4.3260	2989	3724
39.33	25.91	32.97	4.4410	3012	3770
39.11	26.16	33.14	4.6050	3023	3816
38.90	26.42	33.25	4.7190	3046	3863
38.68	26.67	33.37	4.8330	3068	3909
38.01	27.43	33.76	5.2240	3119	4047
37.34	28.19	34.15	5.6130	3169	4184
36.44	29.21	34.65	6.1110	3234	4367

Table A.11b **J-resistance test data for Compact Specimen F33-4-SS-2**
tested at 288 C (550 F); English units

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Extension, inch	J, <u>inch-lb</u> inch²	J_M, <u>inch-lb</u> inch²
198	0.0015	1.1234	0.0000	0	0
1838	0.0066	1.1234	0.0000	13	13
2899	0.0099	1.1234	0.0000	33	33
4286	0.0317	1.1234	0.0000	230	230
5630	0.1184	1.1234	0.0000	1314	1314
7055	0.2424	1.1234	0.0000	3298	3298
8444	0.4067	1.1234	0.0000	6511	6511
9828	0.6870	1.1234	0.0000	12972	12972
9862	0.7085	1.1336	0.0102	13301	13500
9867	0.7124	1.1358	0.0124	13354	13597
9884	0.7686	1.1581	0.0347	14288	14999
9846	0.7856	1.1671	0.0437	14523	15432
9811	0.8037	1.1782	0.0548	14733	15893
9772	0.8218	1.1872	0.0638	14992	16361
9726	0.8384	1.1962	0.0728	15209	16791
9681	0.8525	1.2051	0.0817	15360	17157
9637	0.8608	1.2095	0.0861	15467	17375
9609	0.8657	1.2139	0.0905	15486	17502
9554	0.8745	1.2184	0.0950	15605	17733
9521	0.8838	1.2229	0.0995	15736	17978
9481	0.8931	1.2274	0.1040	15865	18223
9436	0.9023	1.2340	0.1106	15935	18463
9411	0.9063	1.2362	0.1128	15982	18569
9354	0.9155	1.2407	0.1173	16106	18812
9325	0.9199	1.2429	0.1195	16163	18928
9294	0.9248	1.2452	0.1218	16232	19058
9233	0.9341	1.2497	0.1263	16355	19303
9204	0.9385	1.2520	0.1286	16410	19419
8938	0.9800	1.2782	0.1548	16732	20477
8906	0.9849	1.2805	0.1571	16797	20606
8878	0.9893	1.2827	0.1593	16848	20722
8857	0.9937	1.2849	0.1615	16900	20838
8786	1.0100	1.2937	0.1703	17067	21265
8739	1.0200	1.2982	0.1748	17196	21530
8692	1.0300	1.3047	0.1813	17263	21792
8645	1.0400	1.3092	0.1858	17390	22057
8596	1.0500	1.3137	0.1903	17516	22322
8446	1.0800	1.3291	0.2057	17812	23106
8298	1.1100	1.3444	0.2210	18095	23891
8099	1.1500	1.3640	0.2406	18468	24935

Table A.12a Test data from C(T) Specimen F33-4-SSS-1
(Slant-notch with angle of 55 degrees from specimen face, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	$J_{nom}^{(a)}$, kJ/m ²	J_i , kJ/m ²	J_D	J_{iii} , kJ/m ²	$J_{tot}^{(b)}$, kJ/m ²	J_m , kJ/m ²
12.15	0.13	26.67	0.00	3.3	1.8		0.9	2.7	3.3
18.90	0.38	26.67	0.00	20.0	11.0		5.4	16.4	20.0
23.15	1.27	26.67	0.00	99.3	54.6		26.7	81.3	99.3
28.82	3.30	26.67	0.00	323.1	177.7		86.9	264.6	323.1
34.49	6.10	26.67	0.00	698.1	384.0		187.8	571.7	698.1
39.89	10.16	26.67	0.00	1338.8	736.3		360.1	1096.5	1338.8
40.30	10.67	26.76	0.09	1417.9	779.8		381.4	1161.3	1424.9
40.50	11.18	27.01	0.34	1484.7	816.6		399.4	1216.0	1511.4
40.03	12.19	27.61	0.94	1606.7	883.7		432.2	1315.9	1684.7
39.49	12.70	27.98	1.31	1660.7	913.4		446.7	1360.1	1772.0
39.01	13.21	28.34	1.67	1713.2	942.3		460.9	1403.1	1859.3
38.68	14.22	29.05	2.38	1815.0	998.3		488.2	1486.5	2033.7
37.80	15.24	29.78	3.11	1910.7	1050.9		514.0	1564.9	2209.9
37.33	16.51	30.69	4.02	2024.1	1113.3		544.5	1657.7	2431.5
36.99	17.15	31.13	4.46	2082.1	1145.2		560.1	1705.2	2546.2
36.45	17.78	31.56	4.89	2139.9	1176.9		575.6	1752.6	2661.8
35.91	18.67	32.15	5.48	2218.8	1220.3		596.9	1817.2	2823.8
35.17	19.05	32.40	5.73	2252.6	1238.9		605.9	1844.9	2894.4
34.76	19.68	32.82	6.15	2304.6	1267.5		619.9	1887.5	3010.7
34.09	20.32	33.25	6.58	2354.5	1295.0		633.4	1928.3	3127.6
33.41	20.95	33.67	7.00	2402.7	1321.5		646.3	1967.8	3244.5
33.01	21.59	34.07	7.40	2450.4	1347.7		659.2	2006.9	3361.9
32.33	22.23	34.49	7.82	2495.1	1372.3		671.2	2043.5	3479.7
31.39	22.86	34.91	8.24	2533.9	1393.6		681.6	2075.3	3596.9
30.38	23.50	35.34	8.67	2568.3	1412.6		690.9	2103.4	3712.8
29.70	24.13	35.77	9.10	2599.1	1429.5		699.2	2128.7	3828.1
29.02	24.76	36.20	9.53	2627.2	1445.0		706.7	2151.7	3943.3
28.35	25.40	36.63	9.96	2651.8	1458.5		713.3	2171.8	4058.5
27.67	26.03	37.11	10.44	2662.2	1464.2		716.1	2180.3	4172.6
27.00	26.67	37.56	10.89	2676.0	1471.8		719.8	2191.6	4287.5
26.12	27.31	38.02	11.35	2684.8	1476.6		722.2	2198.9	4402.0
25.45	27.94	38.41	11.74	2708.2	1489.5		728.5	2218.0	4518.0
24.91	28.58	38.79	12.12	2732.0	1502.6		734.9	2237.5	4634.4
24.30	29.21	39.16	12.49	2755.8	1515.7		741.3	2257.0	4751.1
23.83	29.84	39.52	12.85	2778.4	1528.1		747.4	2275.5	4868.2
23.22	30.48	39.87	13.20	2800.2	1540.1		753.3	2293.4	4985.7

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

Table A.12b Test data from C(T) Specimen F33-4-SSS-1
(Slant-notch with angle of 55 degrees from specimen face, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		J_{III} , lb/inch	$J_{tot}^{(b)}$, lb/inch	J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_I , lb/inch			
3792	0.0010	1.0438	0.0000	5	3	1	4	5
3971	0.0112	1.0438	0.0000	116	64	31	95	116
5309	0.0913	1.0438	0.0000	1150	633	309	942	1150
6650	0.1987	1.0438	0.0000	2938	1616	790	2406	2938
7946	0.3455	1.0438	0.0000	5921	3257	1593	4849	5921
9261	0.5713	1.0458	0.0020	11306	6218	3041	9260	11330
9302	0.5864	1.0513	0.0075	11606	6383	3122	9505	11719
9312	0.5913	1.0533	0.0095	11701	6436	3148	9583	11846
9296	0.6587	1.0815	0.0377	12952	7124	3484	10608	13588
9226	0.6851	1.0951	0.0513	13388	7363	3601	10965	14284
9075	0.7251	1.1179	0.0741	13985	7692	3762	11454	15336
9016	0.7388	1.1259	0.0821	14183	7801	3815	11616	15701
8957	0.7510	1.1335	0.0897	14347	7891	3859	11750	16027
8883	0.7642	1.1418	0.0980	14519	7985	3906	11891	16379
8788	0.7783	1.1506	0.1068	14698	8084	3954	12038	16754
8734	0.7866	1.1557	0.1119	14808	8144	3983	12128	16976
8673	0.7959	1.1612	0.1174	14930	8211	4016	12228	17224
8346	0.8462	1.1927	0.1489	15486	8517	4166	12683	18524
8316	0.8506	1.1957	0.1519	15529	8541	4177	12718	18641
8254	0.8599	1.2021	0.1583	15614	8588	4200	12788	18886
8197	0.8687	1.2085	0.1647	15686	8627	4220	12847	19118
8121	0.8818	1.2183	0.1745	15782	8680	4245	12925	19462
8055	0.8955	1.2281	0.1843	15890	8740	4274	13014	19822
7988	0.9097	1.2377	0.1939	16015	8808	4308	13116	20197
7906	0.9263	1.2469	0.2031	16212	8917	4361	13278	20639
7784	0.9497	1.2601	0.2163	16469	9058	4430	13488	21258
7714	0.9629	1.2674	0.2236	16616	9139	4470	13609	21609
7644	0.9761	1.2747	0.2309	16760	9218	4508	13726	21961
7573	0.9897	1.2823	0.2385	16902	9296	4547	13843	22322
7389	1.0250	1.3031	0.2593	17207	9464	4629	14093	23244
7249	1.0500	1.3178	0.2740	17412	9577	4684	14260	23902
7104	1.0750	1.3324	0.2886	17606	9683	4736	14419	24559
6959	1.1000	1.3470	0.3032	17787	9783	4785	14568	25214
6814	1.1250	1.3614	0.3176	17959	9877	4831	14708	25869
6669	1.1500	1.3757	0.3319	18120	9966	4874	14840	26522
6523	1.1750	1.3899	0.3461	18272	10050	4915	14965	27173
6378	1.2000	1.4040	0.3602	18412	10127	4953	15079	27823
6173	1.2350	1.4235	0.3797	18584	10221	4999	15220	28722

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_I + J_{III}$.

Table A.13a Test data from C(T) Specimen F33-4-SSS-2
(Slant-notch with angle of 55 degrees from specimen face, test at 288 C; SI units)

Load, kN	Load-Line Displacement, mm	Crack Length, mm	Growth, mm	J_D		J_{III} , kJ/m ²	$J_{tot}^{(b)}$, kJ/m ²	J_m , kJ/m ²
				$J_{nom}^{(a)}$, kJ/m ²	J_I , kJ/m ²			
17.07	0.03	26.51	0.00	0.9	0.5	0.2	0.7	0.9
17.87	0.28	26.51	0.00	20.3	11.2	5.5	16.6	20.3
23.89	2.32	26.51	0.00	201.5	110.8	54.2	165.0	201.5
29.92	5.05	26.51	0.00	514.6	283.0	138.4	421.5	514.6
35.76	8.78	26.51	0.00	1036.9	570.3	278.9	849.2	1036.9
41.67	14.51	26.56	0.05	1980.0	1089.0	532.6	1621.6	1984.3
41.86	14.90	26.70	0.19	2032.7	1118.0	546.8	1664.8	2052.3
41.90	15.02	26.75	0.24	2049.1	1127.0	551.2	1678.2	2074.5
41.83	16.73	27.47	0.96	2268.3	1247.6	610.2	1857.7	2379.7
41.52	17.40	27.82	1.30	2344.7	1289.6	630.7	1920.3	2501.7
40.84	18.42	28.39	1.88	2449.2	1347.1	658.8	2005.9	2685.8
40.57	18.77	28.60	2.09	2483.9	1366.1	668.2	2034.3	2749.8
40.31	19.08	28.79	2.28	2512.6	1381.9	675.9	2057.8	2806.8
39.97	19.41	29.00	2.49	2542.8	1398.5	684.0	2082.6	2868.4
39.55	19.77	29.23	2.71	2574.2	1415.8	692.5	2108.3	2934.2
39.30	19.98	29.35	2.84	2593.3	1426.3	697.6	2123.9	2973.0
39.03	20.22	29.49	2.98	2614.6	1438.0	703.3	2141.4	3016.4
37.56	21.49	30.29	3.78	2712.0	1491.6	729.5	2221.1	3244.2
37.42	21.60	30.37	3.86	2719.6	1495.8	731.6	2227.4	3264.6
37.14	21.84	30.53	4.02	2734.6	1504.0	735.6	2239.6	3307.6
36.88	22.07	30.70	4.18	2747.1	1510.9	739.0	2249.9	3348.2
36.55	22.40	30.94	4.43	2764.0	1520.2	743.5	2263.7	3408.3
36.25	22.75	31.19	4.68	2782.8	1530.5	748.6	2279.1	3471.5
35.94	23.11	31.44	4.93	2804.8	1542.6	754.5	2297.1	3537.2
35.58	23.53	31.67	5.16	2839.2	1561.6	763.7	2325.3	3614.5
35.03	24.12	32.01	5.49	2884.3	1586.4	775.9	2362.2	3722.9
34.71	24.46	32.19	5.68	2910.0	1600.5	782.8	2383.3	3784.5
34.40	24.79	32.38	5.86	2935.3	1614.4	789.6	2404.0	3846.0
34.08	25.14	32.57	6.06	2960.1	1628.1	796.3	2424.3	3909.3
33.25	26.03	33.10	6.59	3013.5	1657.4	810.6	2468.1	4070.8
32.62	26.67	33.47	6.96	3049.3	1677.1	820.3	2497.4	4186.0
31.97	27.31	33.84	7.33	3083.3	1695.8	829.4	2525.2	4301.0
31.31	27.94	34.21	7.70	3115.0	1713.3	837.9	2551.2	4415.8
30.66	28.58	34.58	8.07	3145.1	1729.8	846.0	2575.8	4530.4
30.01	29.21	34.94	8.43	3173.4	1745.4	853.6	2599.0	4644.8
29.35	29.84	35.30	8.79	3200.0	1760.0	860.8	2620.8	4758.9
28.70	30.48	35.66	9.15	3224.6	1773.5	867.4	2640.9	4872.8
27.78	31.37	36.16	9.64	3254.6	1790.0	875.5	2665.5	5030.1

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_I + J_{III}$.

Table A.13b Test data from C(T) Specimen F33-4-SSS-2
(Slant-notch with angle of 55 degrees from specimen face, test at 288 C; English units)

Load, lb	Load-Line Displacement, inch	Crack Length, inch	Crack Growth, inch	J_D		$J_{tot}^{(b)}$		J_m lb/inch
				$J_{nom}^{(a)}$, lb/inch	J_i , lb/inch	J_{iii} , lb/inch	$J_{tot}^{(b)}$, lb/inch	
2700	0.0050	1.0500	0.0000	19	10	5	16	19
4200	0.0150	1.0500	0.0000	114	63	31	93	114
5145	0.0500	1.0500	0.0000	567	312	153	464	567
6405	0.1300	1.0500	0.0000	1845	1015	496	1511	1845
7665	0.2400	1.0500	0.0000	3986	2192	1072	3265	3986
8865	0.4000	1.0500	0.0000	7644	4204	2056	6260	7644
8955	0.4200	1.0537	0.0037	8096	4453	2178	6631	8136
9000	0.4400	1.0635	0.0135	8478	4663	2281	6943	8630
8895	0.4800	1.0871	0.0371	9174	5046	2468	7514	9620
8775	0.5000	1.1014	0.0514	9483	5216	2551	7767	10118
8670	0.5200	1.1158	0.0658	9782	5380	2631	8011	10617
8595	0.5600	1.1438	0.0938	10363	5700	2788	8487	11613
8400	0.6000	1.1725	0.1225	10910	6000	2935	8935	12618
8295	0.6500	1.2081	0.1581	11557	6356	3109	9465	13884
8220	0.6750	1.2255	0.1755	11889	6539	3198	9737	14539
8100	0.7000	1.2425	0.1925	12219	6720	3287	10007	15199
7980	0.7350	1.2658	0.2158	12669	6968	3408	10376	16124
7815	0.7500	1.2756	0.2256	12862	7074	3460	10534	16527
7725	0.7750	1.2923	0.2423	13159	7237	3540	10777	17191
7575	0.8000	1.3090	0.2590	13444	7394	3616	11011	17859
7425	0.8250	1.3254	0.2754	13720	7546	3691	11237	18526
7335	0.8500	1.3415	0.2915	13992	7696	3764	11459	19197
7185	0.8750	1.3578	0.3078	14247	7836	3832	11668	19869
6975	0.9000	1.3746	0.3246	14468	7957	3892	11849	20538
6750	0.9250	1.3914	0.3414	14665	8066	3945	12011	21200
6600	0.9500	1.4083	0.3583	14841	8163	3992	12155	21858
6450	0.9750	1.4252	0.3752	15002	8251	4036	12287	22516
6300	1.0000	1.4422	0.3922	15142	8328	4073	12401	23174
6150	1.0250	1.4610	0.4110	15201	8361	4089	12450	23825
6000	1.0500	1.4789	0.4289	15280	8404	4110	12514	24482
5805	1.0750	1.4970	0.4470	15330	8432	4124	12555	25136
5655	1.1000	1.5123	0.4623	15464	8505	4160	12665	25798
5535	1.1250	1.5272	0.4772	15600	8580	4196	12776	26462
5400	1.1500	1.5416	0.4916	15736	8655	4233	12888	27129
5295	1.1750	1.5559	0.5059	15865	8726	4268	12993	27797
5160	1.2000	1.5698	0.5198	15989	8794	4301	13095	28468

(a) J_{nom} uses ASTM E1152 J_D and ignores the fact that the notch is slanted.

(b) $J_{tot} = J_i + J_{iii}$.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This effort evaluated the fracture toughness of austenitic steel submerged-arc weld (SAW) fusion lines. The incentive was to explain why cracks grow into the fusion line in many pipe tests conducted with cracks initially centered in SAWs. The concern was that the fusion line may have a lower toughness than the SAW.

It was found that the fusion line, J_{Ic} was greater than the SAW toughness but much less than the base metal. Of greater importance may be that the crack growth resistance (J_{D-R}) of the fusion line appeared to reach a steady-state value, while the SAW had a continually increasing J_{D-R} curve. This explains why the cracks eventually turn to the fusion line in the pipe experiments. A method of incorporating these results would be to use the weld metal J-R curve up to the fusion-line steady-state J value. These results may be more important to LBB analyses than the ASME flaw evaluation procedures, since there is more crack growth with through-wall cracks in LBB analyses than for surface cracks in pipe flaw evaluations.

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