Summary of Mechanical Properties

Final Report 277-T-08

For Project

Weld Design, Testing, and Assessment Procedures for High Strength Pipelines

Prepared for the

Design, Materials, and Construction Technical Committee of
Pipeline Research Council International, Inc.
Project MATH-1 Catalog No. L5XXXX

and

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety
DOT Project BAA DTHP56-07-0001

Prepared by
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CANMET Materials Technology Laboratory

September 2011

This research was funded in part under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration's Pipeline Safety Research and Development Program. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, or the U.S. Government.

CANMET Materials Technology Laboratory

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CANMET Report No. 2011-08(TR)

September 2011

Catalog No. L5XXXX

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Version	Date of Last Revision	Date of Uploading	Comments
2	March 2011	4 April 2011	References to be inserted after review.
3	September 2011	30 September 2011	

This report is furnished to Pipeline Research Council International, Inc. (PRCI) under the terms of PRCI contract [277-PR-348-074512] between PRCI and the MATH-1 contractors:

- Electricore (prime contractor),
- Center for Reliable Energy Systems, CANMET, NIST, and The Lincoln Electric Company (sub-contractors).

Pipeline Research Council International Catalog No. L5XXXX

PRCI Reports are Published by Technical Toolboxes, Inc.

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FINAL REPORT STRUCTURE

Focus Area 1 - Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines		
Report #	**Description**	**Lead Authors**
277-T-01	Background of Linepipe Specifications	CRES/CANMET
277-T-02	Background of All-Weld Metal Tensile Test Protocol	CANMET/Lincoln
277-T-03	Development of Procedure for Low-Constraint Toughness Testing Using a Single-Specimen Technique	CANMET/CRES
277-T-04	Summary of Publications: Single-Edge Notched Tension SE(T) Tests	CANMET
277-T-05	Small Scale Tensile, Charpy V-Notch, and Fracture Toughness Tests	CANMET/NIST
277-T-06	Small Scale Low Constraint Fracture Toughness Test Results	CANMET/NIST
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277-S-01	Summary Report 277 Weld Design, Testing, and Assessment Procedures for High Strength Pipelines	CRES

Focus Area 2 - Development of Optimized Welding Solutions for X100 Linepipe Steel		
Report #	**Description**	**Lead Authors**
278-T-01	State of The Art Review	Lincoln
278-T-02	Material Selection, Welding and Weld Monitoring	Lincoln/CANMET
278-T-03	Microstructure and Hardness Characterization of Girth Welds	CANMET/Lincoln
278-T-04	Microstructure and Properties of Simulated Weld Metals	CANMET/Lincoln
278-T-05	Microstructure and Properties of Simulated Heat Affected Zones	CANMET/Lincoln
278-T-06	Essential Welding Variables	Lincoln/CANMET
278-T-07	Thermal Model for Welding Simulations	CRES/CANMET
278-T-08	Microstructure Model for Welding Simulations	CRES/CANMET
278-T-09	Application to Other Processes	Lincoln/CANMET
278-S-01	Summary Report 278 Development of Optimized Welding Solutions for X100 Line Pipe Steel	Lincoln

EXECUTIVE SUMMARY

This is the last report of a series of seven reports detailing the small-scale mechanical testing performed on the trial welds in this consolidated program. This report summarizes and compares the results of all of the mechanical tests applied primarily to welds of rounds 1 and 2, including tensile results and their correlation with microstructure, Charpy test results, conventional (through-thickness-notched) toughness tests, and low-constraint toughness tests.

The report contains a summary of the mechanical properties of the experimental single and dual torch GMAW-P X100 pipe welds prepared for this consolidated program. It summarizes the detailed results reported in Final Reports 277-T-05, 277-T-06 and 277-T-07. The intent of this summary is to provide insight and understanding of the significance of the results and the implications for mechanical testing of weldments to extract properties essential for strain-based design (SBD).

Tensile properties of a pipe can vary significantly through the thickness, and even more in the vicinity of a weld. It is important to use a tensile test specimen that samples as much as the weld metal as possible in order to adequately average the properties across the entire pipe. As part of this project, CANMET developed an all-weld metal tensile test protocol which discusses this process.

It has been shown in the work for this program that good notch toughness values can be achieved in high strength welds. However, for the materials tested there was a tendency for failures in the heat affected zone (HAZ) by brittle cleavage in conventional (high-constraint) SE(B) tests, especially at -20˚C and below. Cleavage failures were less frequent in low-constraint (tensile loaded) tests.

Low-constraint tests of single-edge tension SE(T) specimens were developed to provide resistance curves for prediction of curved-wide-plate performance. The average ratio of the low-constraint SE(T) toughness (J at 0.5 mm crack growth for 3 mm initial crack size) to the conventionally measured high-constraint SE(B) toughness (J at maximum load) was about 1.7 if no cleavage occurred; however, many of the HAZ samples suffered brittle failure in high-constraint tests. For the shallow-crack specimens used in this project (a/W=0.17 to 0.35), the toughness was higher in tension than in bending.

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1 INTRODUCTION

This is the last report of a series of seven reports detailing the small-scale mechanical testing performed on the trial welds in this consolidated program.

The first report, 277-T-02, describes the development of procedures for measuring tensile properties of the welds; the second, 277-T-03, describes the development of a low-constraint toughness test using a single-edge notched tensile SE(T) specimen. The third, 277-T-04, highlights the principal results of preliminary application of the toughness test procedure that have been published in a series of papers in the open literature. The fourth, 277-T-05, presents the results of tensile tests and conventional toughness tests, both notch toughness (Charpy) and fracture toughness (through-thickness-notched specimens), and discusses correlation with microstructure. The fifth, 277-T-06, reports the results of application of the low-constraint tensile toughness test, supplemented with results of shallow-notch bend tests, including tests on base metal, weld metal, and HAZ. The sixth, 277-T-07, summarizes and discusses the toughness results of the previous report 277-T-06. Finally, the seventh report, 277-T-08, summarizes and compares the results of all of the mechanical tests applied primarily to welds of rounds 1 and 2, including tensile results and their correlation with microstructure, Charpy test results, conventional (through-thickness-notched) toughness tests, and low-constraint toughness tests. The primary objective of the small-scale testing work has been to develop and apply techniques for measuring tensile and toughness properties that are relevant to the assessment of flaws in welds using strain-based design. In particular, the average toughness properties for flaw depths of 3 and 6 mm, reported in 277-T-07, are intended to be used in the interpretation of wide plate tests carried out in the course of the project.

This report, 277-T-08, contains a summary of the mechanical properties of the experimental single and dual torch GMAW-P X100 pipe welds prepared for the two projects within this consolidated program (i) Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines and (ii) Development of Optimized Welding Solutions for X100 Line Pipe Steel. It summarizes the detailed results reported in Final Reports 277-T-05, 277-T-06 and 277-T-07 [1-3]. The intent of this summary is to provide insight and understanding of the significance of the results and the implications for mechanical testing of weldments to extract properties essential for strain based design (SBD).

2 OVERVIEW OF RESULTS

2.1 TENSILE PROPERTIES

SBD introduces a requirement to quantify longitudinal tensile properties as well as the transverse properties required for pressure containment. In SBD, the common approach to assurance of girth weld tensile integrity is to require, in addition to bend tests to ensure ductility and quality, the specification of a longitudinal strap tensile test to verify that the ultimate tensile strength (UTS) of the weldment is at least equal to the minimum specified UTS. While this criterion has served well for conventional service, for more demanding applications it is prudent to evaluate the risk of strain concentration in the weld.

The desired property is resistance to longitudinal tensile strain, and this is best assessed by knowledge of the stress-strain curve of the various regions in the weld. However, the stress-strain response is highly affected by local constraints that are sensitive to weld geometry, in particular the width of weld metal and HAZ and the bevel angle. The weld region is highly inhomogeneous, and this is reflected in a wide range of mechanical properties. For example, the hardness varies significantly both across the weld (longitudinal to the pipe axis) and through the thickness. In order to have a specimen with a long enough gauge length to measure strain in narrow regions like the HAZ with reasonable accuracy, attempts have been made elsewhere to machine and test micro-tensile specimens. However, this is an exacting task and does not reflect the effect of neighbouring material on modifying the local stress and strain, for example by affecting stress tri-axiality. Moreover, such specimens measure properties in the "long" direction of the microstructure, which is parallel to the weld rather than transverse to it (i.e. longitudinal to the pipe axis) which is the direction of interest for axial strain. Fortunately, it has been shown that the differences between transverse and longitudinal properties are small, at least for the weld metal [4].

Hardness can give useful insight into mechanical properties. It is well established that hardness of steels correlates well with UTS. The hardness maps reported in Final Report 278-T-03 [5] show the different weld passes and resulting property variations in a striking fashion. An example is shown in Figure 1 in which the different weld passes may be clearly discerned. Note for the single-torch weld (left) the region of lower hardness under the cap. In both cases the root pass has lower hardness, as expected, and there is significant softening in the HAZ [1].

In the current project, tests have focused on measurement of tensile properties of the weld using round and strip tensile specimens with their axes in the longitudinal weld (transverse pipe) direction. The results reveal a variation of weld metal yield and tensile strength through the thickness of the single-torch welds, with the strength of the weld metal at the outer diameter (OD) being significantly less than that at the inner diameter (ID); the difference in yield strength measured over the dimension of tensile specimens can be as much as 15 %, although on a micro-scale the variation can be even larger as evidenced by microhardness maps. Strip tensile results average the two stress-strain curves, as expected. The stress-strain curves of the weld metal show a significantly sharper yield point than the pipe, especially for the ID specimens. The UTS variation is much less marked than the variation in yield strength, being only a few percent. The dual torch welds show much less variation in properties through the thickness, with negligible difference between ID and OD specimens. Uniform elongation in all cases was of the order of 7-8 %. For the pipes used in this project, these properties correspond to strength overmatch (based on the UTS of strip tensile specimens) ranging between only 1.06 and 1.08 for the single-torch welds and 1.02 to 1.05 for the dual-torch welds. The overmatch is slightly higher when based on the yield rather than the tensile strength; this is consistent with the "round-house" shape of the pipe stress-strain curves and the more sharply-yielding weld metal curves. A protocol has been developed for standard measurement of weld metal properties based on the strip tensile design [6].

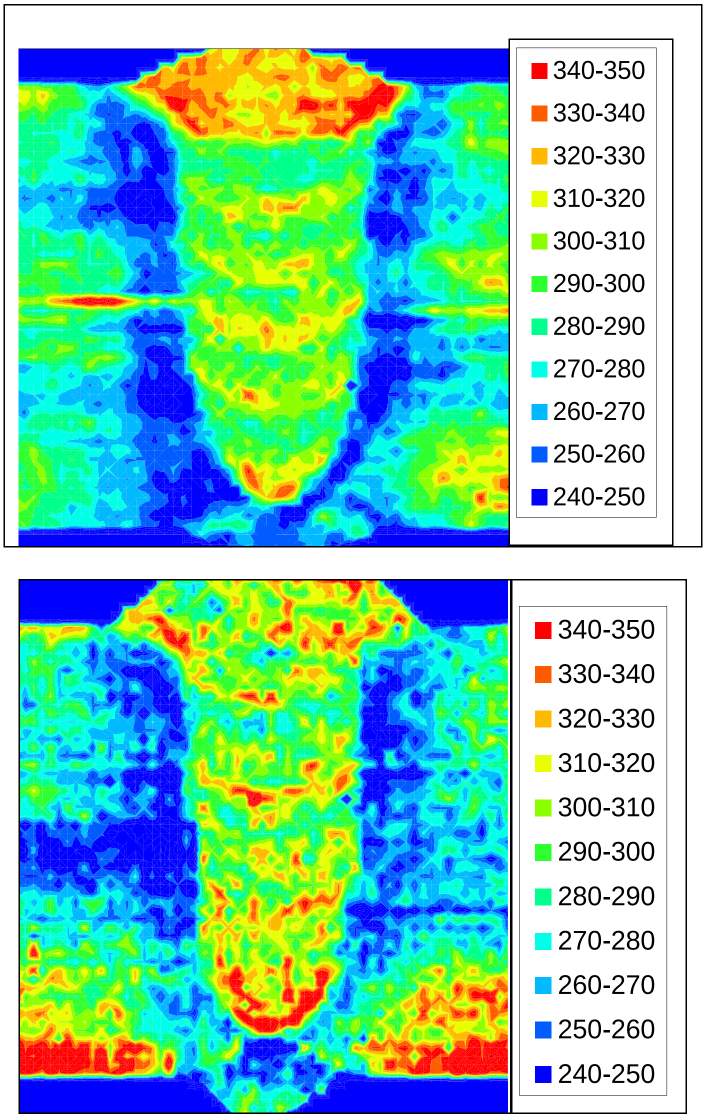

Figure 1. Hardness maps of single-torch (top) and dual-torch (bottom) welds [5]. Scale unit = VHN_{300}.

2.2 CVN PROPERTIES

Charpy-V-notch (CVN) properties were measured for both single- and dual-torch welds. Weld metal specimens were biased toward the cap (OD) or the root (ID) as shown in Figure 6 in Final Report 277-T-05 [1]. HAZ specimens were biased toward the OD, and base metal specimens were from the middle of the wall thickness. The data could be reasonably fit using a hyperbolic tangent function, and the curve-fit parameters are shown in Table 1.

Table 1. CVN properties of base metal, single-torch (R1) and dual-torch (R2) welds

Identification	Lower Shelf Energy, J	Upper Shelf Energy, J	Transition Temperature, °C
X100 Pipe (100-5)	15	300	-70
807-F (R1) WMC-Cap	15	165	-70
807-F (R1) WMC-Root	20	245	-67
807-F (R1) HAZ-FL	13	237	-69
883-D (R2) WMC-Cap	20	145	-70
883-D (R2) WMC-Root	25	175	-69
883-D (R2) HAZ-FL	20	250	-35

The CVN properties are good, with high upper-shelf energies and transition temperatures (defined as the temperature for CVN at the middle of the transition region) near -70˚C. The exception is the HAZ of the dual-torch weld (R2), for which the transition temperature is -35˚C although the upper-shelf energy is high.

2.3 HIGH-CONSTRAINT SE(B) PROPERTIES

Results of standard high-constraint SE(B) tests are reported in Final Report 277-T-05 [1]. Measurements were made for both single- and dual-torch welds, at room temperature and at -20 and -40˚C. The intent of this set of measurements was to obtain toughness data as it would be measured following the current convention for comparison with toughness measured under low constraint, simulating service conditions. Note that the specimen geometry for these measurements was Bx2B (with the specimen thickness B being the plate thickness), plain-sided, with the notch placed through-thickness. There are thus a number of differences with the low-constraint tests, so comparisons must be made with caution.

As reported in Table 12 and Table 13 of final report 277-T-05 [1] (see extracted J values for Bx2B specimens in Table 3 below), the weld-metal-centreline specimens failed by ductile crack propagation with generally good toughness (close to 0.2 mm CTOD at maximum load) at all temperatures. The WM toughness was less than that of the pipe BM, although this should not be surprising. Most of the HAZ specimens of round 1 and 2 welds, on the other hand, showed brittle cleavage (although generally after some ductile crack growth, especially for the dual-torch welds). Nevertheless, CTOD values were generally quite good (0.14 mm or higher, except for one low value of 0.04 mm for a single-torch weld specimen at -20˚C). In contrast, four of five HAZ specimens of round 3 welds showed maximum-load behaviour at -20 °C.

2.4 LOW-CONSTRAINT SE(T), SE(B) PROPERTIES

As reported in final reports 277-T-06 and 277-T-07 [2, 3], low-constraint toughness tests have been performed on bars from welds of both single-torch and double-torch variants, including both rolled and 5G welds. The specimen geometry was chosen to have a square cross-section (BxB) with B being as close as possible to the pipe wall thickness (allowing for machining to eliminate curvature and high/low).

For tensile tests, the “daylight” (gauge) length between the grips was ten times the cross-section dimension, which was determined from preliminary finite element analysis (FEA) to give good constraint matching to surface circumferential flaws in pipe as described in the companion Final Report 277-T-03 [7]. The SE(T) test procedure may be found in the Summary Report 277-S-01 [8]. Target crack sizes were chosen to be 3 and 6 mm, corresponding roughly to single and double pass heights. Tests were performed at room temperature, -20˚C and -40˚C. To promote straight-fronted crack growth, side grooves were used with a total side-groove depth in most cases of 15 % of thickness. To measure R curves, crack growth was measured using elastic unloading compliance; this technique gave good agreement with crack size measured optically on the fracture surface. Duplicate tests were performed for most conditions; agreement was generally good (scatter band within about 10 %). In total, more than 100 tests were done in this program.

SE(B) tests on BxB specimens notched to nominal crack size of 3 mm or 6 mm in the BM, WM or HAZ regions were conducted and analysed according to the shallow-notch procedure of ASTM E1820-11. Side grooves were used to promote straight-fronted crack growth.

Both J-resistance and CTOD-resistance curves are reported in the final reports [2, 3]. J values were calculated from the area under the measured load vs. plastic CMOD curves according to the CANMET procedure [8] for SE(T) testing and to ASTM E1820-11 for SE(B) testing. It should be noted that CTOD was calculated from J following the same practice as in ASTM E1820 for both SE(T) and SE(B) results: $J=m\sigma_Y\delta$ where σ_Y is the flow stress (average of yield strength σ_{YS} and ultimate tensile strength σ_{TS}) and m is a parameter that depends on a/W and σ_{YS}/σ_{TS}. Note that for SE(T) specimens, the load-dependance of m for loads above limit load as reported in section 6 of 277-T-04 has been taken into account. Appropriate values of m for SE(B) were taken from E1820 and for SE(T) were determined by FEA [9]. In a region of inhomogeneous properties such as the HAZ, the highest tensile properties in the region have been used following normal practice to ensure conservative CTOD values.

Points of peak load were identified during data analysis, and the corresponding amount of crack growth Δa was noted. The results are shown in Table 2. It is evident that peak load is reached after only a small amount of crack growth, of the order of 5 % of the ligament. The average amount of crack growth is 0.59 mm, with individual values ranging from 0.35 to 1.02 mm. Crack growth at peak load is slightly greater in tension than in bending (averages of 0.63 and 0.51 mm respectively), but in general the peak load is reached after crack growth not far from 0.5 mm in both cases.

Table 2. Crack growth Δa at peak load

Material	Temp.	Target a_0	SE(T) mean Δa	SE(B) mean Δa
BM	RT	3	0.42	-
		6	0.42	0.41
	-20	3	0.43	-
		6	0.29	-
WMR1	RT	3	0.65	0.68
		6	1.02	0.41
	-20	3	0.75	0.56
		6	0.92	0.44
	-40	3	0.92	-
HAZR1	RT	3	0.35	0.64
		6	0.44	0.33
	-20	3	0.56	0.73
		6	0.65	0.4
	-40	3	0.59	-
WMR2	RT	3	0.65	0.53
		6	0.81	0.39
	-20	3	0.87	0.53
		6	0.85	0.55
HAZR2	RT	3	0.57	-
		6	0.53	-
	-20	3	0.54	-
		6	0.69	-

Figure 2 and Figure 3 show the values of J-integral at 0.5 mm crack growth in tension SE(T) and bending SE(B) respectively, calculated from power-law curve fits to the R curves taking all results into account and extrapolating or interpolating to initial crack sizes of 3 and 6 mm (Tables 12 and 13 of Final Report 277-T-07 [3]). There is little difference between the base metal and HAZ toughness, but the weld metal shows significantly lower toughness for both single- and dual-torch welds. Although significant scatter is observed, toughness generally decreases with increasing initial crack length for all materials as anticipated, owing to the dependence of constraint on initial crack length (higher constraint for deeper cracks). There is also a notable difference in shallow-notch toughness between tension and bending, the SE(T) toughness measured in Rounds 1 and 2 being significantly higher than the SE(B) toughness. Indeed, for the WM of Round 3 the SE(T) toughness is over twice as large as the SE(B) toughness (739 vs. 319 kJ/m^2 for 3 mm initial crack depth tested at -20 ºC, reported in 277-T-07).

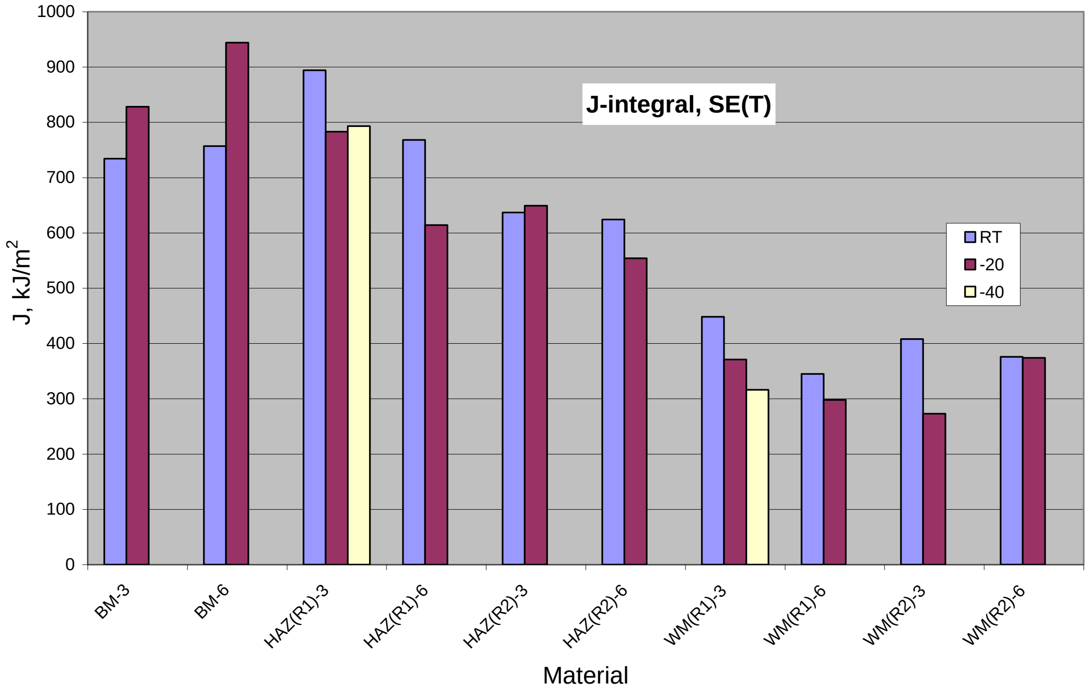

Figure 2. SE(T) J-integral at 0.5 mm crack growth as a function of initial crack size (3 mm and 6 mm) and temperature (RT, -20˚ and -40˚C) for both single-torch (R1) and dual-torch (R2) welds

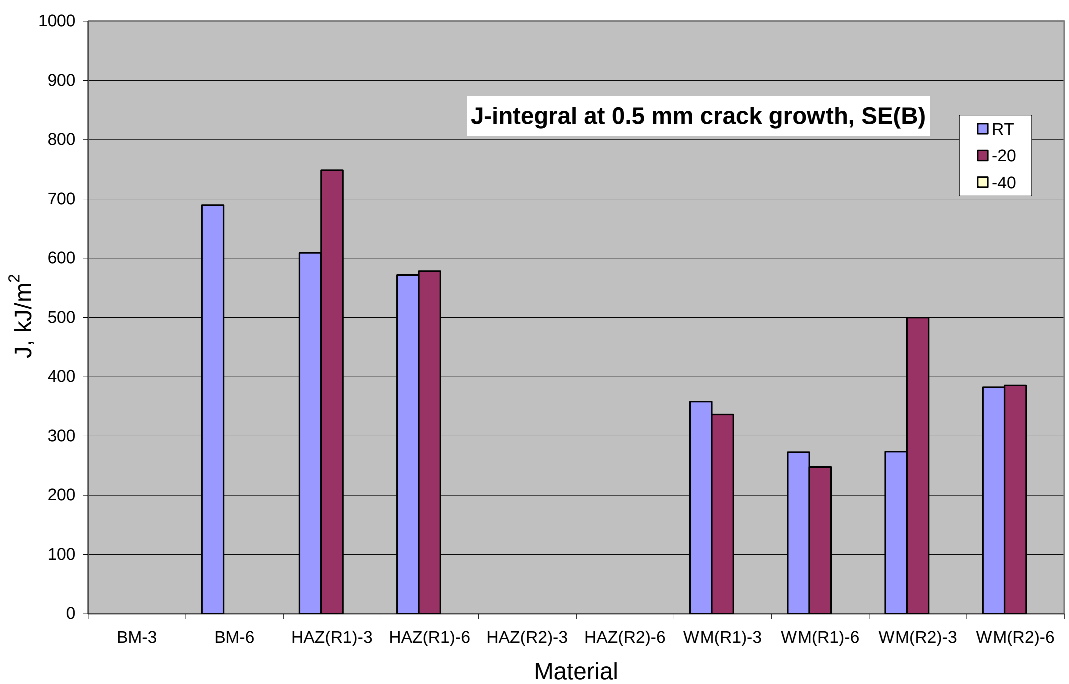

Figure 3. SE(B) J-integral at 0.5 mm crack growth as a function of initial crack size (3 mm and 6 mm) and temperature (RT and -20˚C) for both single-torch (R1) and dual-torch (R2) welds

It is of interest to assess whether CVN data can be used to predict fracture toughness. Figure 4 shows the relation between the J integral (at 0.5 mm crack growth from SE(T) tests at -20˚C and 3 mm initial crack size), versus the upper-shelf Charpy energy (USE). Surprisingly, there is a much better correlation with the USE measured at the weld cap position (open square points) than with the USE from the weld root position (filled triangular points), in spite of the fact that the crack location for the J integral measurements is closer to the root.

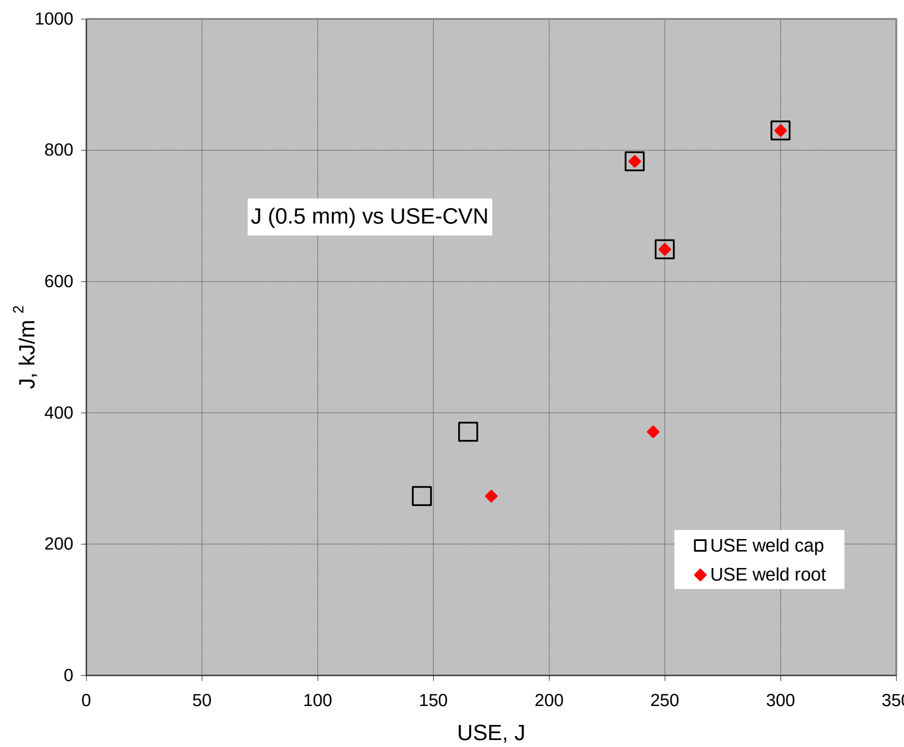

Figure 4. J-integral at 0.5 mm crack growth, -20˚C, 3 mm initial crack size, vs. CVN upper-shelf energy USE

In general, the following conclusions can be drawn from the low-constraint toughness results.

- There is little effect of temperature on the ductile tearing resistance curves.
- The a/W ratio has a small effect on the R curves in tension whereas toughness decreases more consistently as the crack size increases in bending.
- For shallow-crack specimens (a/W=0.17 to 0.35 in this work) the toughness is higher in tension SE(T) compared with bending SE(B).

2.5 COMPARISON OF LOW- AND HIGH-CONSTRAINT PROPERTIES

Table 3 shows J-integral values for both welding variants obtained in conventional high-constraint SE(B) tests and low-constraint SE(T) tests. It must be borne in mind that not only are the specimen geometries and side-grooving different (Bx2B plane-sided vs. BxB side-grooved), but the notch orientation is also different (through-thickness vs. surface). Also, for the “conventional” Bx2B specimens the toughness is taken at maximum load or at onset of brittle fracture, whichever comes first. Thus, although the values of toughness are not strictly comparable, the intent of this comparison is to reveal the differences that would accompany the use of the more relevant low-constraint test in place of the conventional high-constraint test to determine material properties.

Pipeline construction standards usually require that the minimum value measured in three tests be taken as the characteristic toughness. Owing to variability of the number of specimens tested at a given temperature in this work, the lowest measured value is recorded in Table 3 for the Bx2B specimens along with the number of specimens and the performance (c, u or m). For the SE(T) tests, the values are relevant to an initial crack size of 3 mm, and values at 0.5 mm crack growth have been calculated from curve fits to the R curve data, which is the relevant data for strain-based design assuming ductile crack growth. Note, however, that there were a few HAZ cleavage fractures at -20 ºC. Cleavage fracture is a stochastic process and brittle toughness is notoriously scattered. The observation of such fractures in this work is a caution that brittle fracture is possible even in low-constraint tensile-loaded situations, but it should be expected that the toughness under these conditions would be highly variable. In other words, observation of brittle fracture in small-scale tests is cautionary, but does not imply that brittle fracture will necessarily occur for all CWP tests for the same flaw depth and temperature; indeed, this is highly improbable. For ductile flaw growth in CWP tests, the low-constraint ductile R curve will be followed unless brittle fracture intervenes.

Table 3. J-integral values for single- and dual-torch welds measured by conventional high-constraint Bx2B SE(B) tests and low-constraint BxB SE(T) tests

Weld	Single Torch				Dual Torch			
Position	WMC		HAZ		WMC		HAZ	
Temperature °C	J Bx2B SE(B) (kJ/m^2)	J(0.5 mm)* BxB SE(T) (kJ/m^2)	J Bx2B SE(B) (kJ/m^2)	J(0.5 mm)* BxB SE(T) (kJ/m^2)	J Bx2B SE(B) (kJ/m^2)	J(0.5 mm)* BxB SE(T) (kJ/m^2)	J Bx2B SE(B) (kJ/m^2)	J(0.5 mm)* BxB SE(T) (kJ/m^2)
RT	209 (3m)**	448 (2m)	526 (2m)	894 (2m)	292 (2m)	408 (2m)	408 (1m)	637 (2m)
-20	211 (3m)	371 (4m)	69 (2c,2u)	783 (1c,1u,1m)	360 (2m)	273 (2m)	220 (3u)	649 (2m)
-20 (round 3)	247 (6m)	739 (6m)	310 (4m, 1u)	1072 (5m,1u)				
-40	258 (1m)	316 (2m)	271 (2u)	793 (2m)	341 (2m)	-	236 (2u)	-

* for specimens of 3 mm crack size
** 3 denotes three specimens tested: m denotes ductile growth at maximum load; c denotes cleavage before 0.2 mm ductile tearing; u denotes cleavage after at least 0.2 mm crack growth

It is evident that the low-constraint toughness is in general higher than the high-constraint toughness, the average ratio of the two being close to 2.9. However, there is wide variation in this value, ranging between 0.8 and 11.4, with the larger value reflecting the very low toughness of one brittle HAZ fracture at -20 ºC; the median of the ratio of the SE(T) toughness to the Bx2B SE(T) toughness is close to 2. Considering only ductile fractures, the average ratio is 1.7; if a brittle fracture occurred in a high-constraint Bx2B test, the average ratio was 5.2. To summarize, the major effect of performing a high-constraint test is to enhance the likelihood of cleavage. If no brittle fracture occurs, the ratio of the low-constraint to conventional (high-constraint) toughness is about 1.7.

The fact that a higher proportion of the high-constraint tests resulted in cleavage fracture is noteworthy. The weld metal tests were consistently ductile, but the HAZ of both weld variants were susceptible to brittle cleavage – although sometimes at quite high J values. As shown in the table, in high-constraint (standard) tests the HAZ of single-torch welds failed by cleavage in seven out of eleven tests at -20˚C and below, and the HAZ of the dual-torch weld failed by cleavage in all five tests at -20˚C and below. It was also noted that surface notched specimens failed by cleavage more frequently in bending than in tension (BxB specimens SE(B) and SE(T) tested at -20˚C, section 4.1.3 of Final Report 277-T-07 [3]).

3. DISCUSSION

Tensile properties of a pipe can vary significantly through the thickness and around the circumference, and even more in a weld. Variation through the thickness of a weld can be of the order of 15 %, and it is important to average the properties adequately by use of a tensile test specimen that samples as much as possible of the weld metal as in the CANMET weld metal tensile test protocol.

It has been shown in this work that good notch toughness values can be achieved in high-strength welds. However, for the materials tested in this program there was a tendency for failures in the HAZ by brittle cleavage in conventional (high-constraint) SE(B) tests, especially at -20˚C and below. Cleavage failures were less frequent in low-constraint tests.

The low-constraint SE(T) toughness (J at 0.5 mm crack growth for 3 mm initial crack size) was higher than the conventionally-measured high-constraint SE(B) toughness (J at maximum load) in all cases but one, the average ratio being close to 1.7 if no cleavage occurred but close to 5.2 if there was brittle fracture in the high-constraint test. For the shallow-crack BxB specimens used in this project (a/W=0.17 to 0.35) the toughness at 0.5 mm crack growth was higher in tension than in bending.

4. ACKNOWLEDGMENTS

This work is part of a larger consolidated program jointly funded by the Canadian Federal Government Program of Energy Research and Development (PERD), the Pipeline and Hazardous Materials Safety Administration of the U.S. Department of Transportation (DOT), and the Pipeline Research Council International, Inc. (PRCI).

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