Effects of Specimen Geometry and Mode Loading on Crack Growth Resistance Curves of X80 Pipeline Girth Welds

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Abstract This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves. Use of these materials is motivated by the increasing demand in the number of applications for manufacturing high strength pipes for the oil and gas industry including marine applications and steel catenary risers. Testing of the pipeline girth welds employed side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch and varying crack sizes to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. Recently developed compliance functions and η -factors applicable for SE (T) and SE(B) fracture specimens are introduced to determine crack growth resistance data from laboratory measurements of load-displacement records.

Keywords *J*-Resistance Curves, Ductile Fracture, SE(T) Specimen, SE(B) Specimen, Crack Growth

1. Introduction

Fracture mechanics based approaches to describe ductile fracture behavior in structural components rely upon crack growth resistance (J-Δa) curves to characterize crack extension followed by crack instability of the material. These approaches allow the specification of critical crack sizes based on the predicted growth of crack-like defects under service conditions. Current standardization efforts now underway advocate the use of single edge notch tension SE(T) specimens to measure experimental *R*-curves more applicable to high pressure piping systems, including girth welds of marine steel risers.

The primary motivation to use SE(T) fracture specimens in defect assessment procedures for this category of structural components is the strong similarity in crack-tip stress and strain fields which drive the fracture process for both crack configurations. However, while now utilized effectively in fracture testing of pipeline girth welds, some difficulties associated with SE(T) testing procedures, including fixture and gripping conditions, raise concerns about the significance and qualification of measured crack growth resistance curves. While slightly more conservative, testing of shallow-crack bend specimens (which is a nonstandard SE(B) configuration) may become more attractive due to its simpler testing protocol, laboratory procedures and much smaller loads required to propagate the crack.

This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves. Use of these materials is motivated by the increasing demand in the number of applications for manufacturing high strength pipes for the oil and gas industry including marine applications and steel catenary risers. Testing of the pipeline girth welds employed side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch and varying crack sizes to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. Recently developed compliance functions and η-factors applicable for SE (T) and SE(B) fracture specimens are introduced to determine crack growth resistance data from laboratory measurements of load-displacement records

2. *J*-Resistance Curve Measurements Based on the UC Procedure

2.1. Evaluation Procedure of the *J*-Integral

Conventional testing programs to measure crack growth resistance ($J-\Delta a$) curves in metallic materials routinely employ the unloading compliance (UC) method based on a single specimen test. A widely used approach (which forms the basis of current standards such as ASTM E1820 [1]) to evaluate *J* with crack extension follows from an incremental procedure which updates J_e and J_p at each partial unloading point, denoted *k*, during the measurement of the load vs. displacement curve as

$$J^k = J_e^k + J_p^k \tag{1}$$

where the current elastic term is simply given by

$$J_e^k = \left(\frac{K_I^2}{E'}\right)_k \tag{2}$$

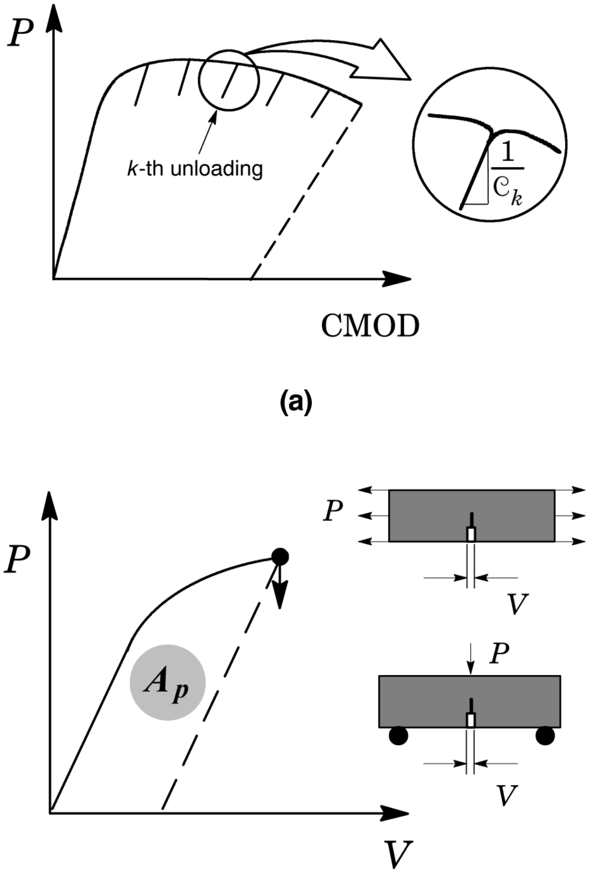
and the current plastic term follows an incremental formulation which is applicable to CMOD data in the form [2,3]

$$J_p^k = \left[J_p^{k-1} + \frac{\eta_{J-CMOD}^{k-1}}{b_{k-1}B_N}\left(A_p^k - A_p^{k-1}\right)\right]\left[1 - \frac{\gamma_{LLD}^{k-1}}{b_{k-1}}\left(a_k - a_{k-1}\right)\right] \tag{3}$$

in which factor γ_{LLD} is evaluated from

$$\gamma_{LLD} = \left[-1 + \eta_{J-LLD}^{k-1} - \left(\frac{b_{k-1}}{W\eta_{J-LLD}^{k-1}}\frac{d\eta_{J-LLD}^{k-1}}{d(a/W)}\right)\right] \tag{4}$$

In the above expressions, K_I is the elastic stress intensity factor for the cracked configuration, A_p is the plastic area under the load-displacement curve, B_N is the net specimen thickness at the side groove roots ($B_N = B$ if the specimen has no side grooves where *B* is the specimen gross thickness), *b* is the uncracked ligament ($b = W - a$, where *W* is the width of the cracked configuration and *a* is the crack length). In writing Eq. (2), plane-strain conditions are adopted such that $E' = E/(1-\nu^2)$ where *E* and ν are the (longitudinal) elastic modulus and Poisson's ratio, respectively. Factor η_J appearing in Eqs. (3) and (4) represents a nondimensional parameter which relates the plastic contribution to the strain energy for the cracked body and *J*. Figure 1 illustrates the essential features of the estimation procedure for the plastic component J_p. Here, we note that A_p (and consequently, η_J) can be defined in terms of load-load line displacement (LLD or Δ) data or load-crack mouth opening displacement (CMOD or V) data. For definiteness, these quantities are denoted η_{J-LLD} and η_{J-CMOD}.



(a)

(b)

Figure 1. (a) Partial unloading during the evolution of load with crack mouth opening displacement (CMOD or *V*); (b) Definition of the plastic area under the load-displacement curve.

The incremental expression for J_p defined by Eq. (3) coupled with Eq. (4) contains two contributions: one is from the plastic work in terms of CMOD and, hence, η_{J-CMOD} and the other due to crack growth correction in terms of LLD by means of η_{J-LLD}. Evaluation of Eqs. (3) and (4) is relatively straightforward provided the two geometric factors, η_{J-CMOD} and η_{J-LLD}, are known. For the clamped SE(T) specimens with $H/W = 10$ and the conventional SE(B) configuration utilized in this study, a convenient polynomial fitting of the results given by Cravero and Ruggieri [4], Ruggieri [5] and Donato and Ruggieri [6] provide the corresponding η-factor equations in the form

$$\eta_{J-CMOD}^{SET} = 1.067 - 1.767\frac{a}{W} + 7.808\left(\frac{a}{W}\right)^2 - 19.269\left(\frac{a}{W}\right)^3 + 15.295\left(\frac{a}{W}\right)^4 - 3.083\left(\frac{a}{W}\right)^5 \quad (5)$$

$$0.2 \le a/W \le 0.7$$

$$\eta_{J-LLD}^{SET} = -0.623 + 9.336\frac{a}{W} - 4.584\left(\frac{a}{W}\right)^2 - 47.963\left(\frac{a}{W}\right)^3 + 87.697\left(\frac{a}{W}\right)^4 - 44.875\left(\frac{a}{W}\right)^5 \quad (6)$$

$$0.2 \le a/W \le 0.7$$

$$\eta_{J-CMOD}^{SEB} = 3.650 - 2.111\frac{a}{W} + 0.341\left(\frac{a}{W}\right)^2 \tag{7}$$

$$0.1 \le a/W \le 0.7$$

$$\eta_{J-LLD}^{SEB} = 0.020 + 18.086\frac{a}{W} - 72.256\left(\frac{a}{W}\right)^2 + 152.225\left(\frac{a}{W}\right)^3 - 159.769\left(\frac{a}{W}\right)^4 + 66.879\left(\frac{a}{W}\right)^5 \tag{8}$$

$$0.1 \le a/W \le 0.7$$

2.2. Crack Extension Estimation

Current testing protocols to measure the crack growth resistance response using a single-specimen test are primarily based on the unloading compliance (UC) technique to obtain accurate estimates of the (current) crack length from the specimen compliance measured at periodic unloadings with increased deformation. Figure 1 illustrates the essential features of the method. The slope of the load-displacement curve during the *k*-th unloading defines the current specimen compliance, denoted C_k, which depends on specimen geometry and crack length. For the clamped SE(T) and SE(B) crack configurations analyzed here, the specimen compliance is most often defined in terms of normalized quantities expressed as [1,4]

$$\mu_{CMOD}^{SET} = \left[1 + \sqrt{EB_e C_{CMOD}}\right]^{-1} \tag{9}$$

and

$$\mu_{CMOD}^{SEB} = \left[1 + \sqrt{\frac{EWB_e C_{CMOD}}{S/4}}\right]^{-1} \tag{10}$$

where μ_{CMOD}^{SET} and μ_{CMOD}^{SEB} define the normalized compliances for the SE(T) and SE(B) specimens. In the above expressions, E is the longitudinal elastic modulus, C_{CMOD} denotes the specimen compliance defined in terms of crack mouth opening displacement ($C_{CMOD} = V/P$ where V is the CMOD and P represents the applied load) and the effective thickness, B_e, is defined by

$$B_e = B - \frac{(B - B_N)^2}{B} \tag{11}$$

By measuring the instantaneous compliance during unloading of the specimen (see Fig. 1), the current crack length follows directly from solving the functional dependence of crack length and specimen compliance in terms of μ_{CMOD}. For the clamped SE(T) specimen and SE(B) configuration analyzed here, the corresponding compliance expressions follow from Cravero and Ruggieri [4] and ASTM E1820 [1] as

$$\left[\frac{a}{W}\right]_{SET} = 1.9215 - 13.2195\mu + 58.7080\mu^2 - 155.2823\mu^3 + 207.3987\mu^4 - 107.9176\mu^5 \quad (12)$$

$$0.1 \le a/W \le 0.7$$

$$\left[\frac{a}{W}\right]_{SEB} = 10.9997 - 3.9504\mu + 2.9821\mu^2 - 3.2141\mu^3 + 51.5164\mu^4 - 113.0310\mu^5 \quad (13)$$

$$0.1 \le a/W \le 0.8$$

3. Experimental Details

3.1. Material Description and Welding Procedures

The material utilized in this study was a high strength, low alloy (HSLA), API grade X80 pipeline steel produced as a base plate using a control-rolled processing route without accelerated cooling. The mechanical properties and strength/toughness combination for this material are mainly obtained by both grain size refinement and second-phase strengthening due to the small-size precipitates in the matrix. The 20-inch pipe with longitudinal seam weld from which the girth weld SE(T) and SE(B) specimens were extracted was fabricated using the UOE process.

The tested weld joint was made from the API X80 UOE pipe having thickness, $t_w = 19$ mm. Girth welding of the pipe was performed using the FCAW process in the 1G (flat) position with a single V-groove configuration in which the root pass was made by GMAW welding. The main weld parameters used for preparation of the test weld using the FCAW process are: i) number of passes 12 (including the root pass made by the GMAW process); ii) welding current 165 A; iii) welding voltage 23 V; iv) average heat input 1.5 kJ/mm. Mathias et al. [7] provide the tensile properties for the tested pipeline girth weld and base material which include: $\sigma_{ys}^{WM} = 715$ MPa, $\sigma_{uts}^{WM} = 750$ MPa, $\sigma_{ys}^{BM} = 609$ MPa, $\sigma_{uts}^{BM} = 679$ MPa. Here, σ_{ys} and σ_{uts} represent the material's yield stress and tensile strength, and WM and BM denote the weld metal and base plate. The degree of weld strength overmatch is ~18% so that mismatch effects on the measured crack growth resistance curves are very small.

3.2. Specimen Geometries

Unloading compliance (UC) tests at room temperature were performed on weld centerline notched SE(T) specimens with fixed-grip loading to measure tearing resistance curves in terms of $J - \Delta a$ data. The clamped SE(T) specimens have a fixed overall geometry and crack length to width ratio defined by $a/W = 0.4$, $H/W = 10$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and clamp distance $H = 148$ mm (refer to Fig. 2(a)). Here, a is the crack depth and W is the specimen width which is slightly smaller than the pipe thickness, t_w. UC tests at room temperature were also conducted on weld centerline notched SE(B) specimens with $a/W = 0.25$ with thickness $B = 14.8$ mm, width $W = 14.8$ mm and span $S = 4W$ (refer to Fig. 2(b)). Conducted as part of a collaborative research program conducted at University of São Paulo on structural integrity asssessment of marine steel catenary risers (SCRs), testing of these specimens focused on the development of accurate procedures to evaluate crack growth resistance data for pipeline girth welds.

All specimens, including the SE(T) configuration, were precracked in bending using a three-point bend apparatus very similar to a conventional three-point bend test. After fatigue precracking, the specimens were side-grooved to a net thickness of ~85% the overall thickness (7.5% side-groove on each side) to promote uniform crack growth and tested following some general guidelines described in ASTM E1820 standard [1]. Records of load vs. crack mouth opening displacements (CMOD) were obtained for the specimens using a clip gauge mounted on knife edges attached to the specimen surface.

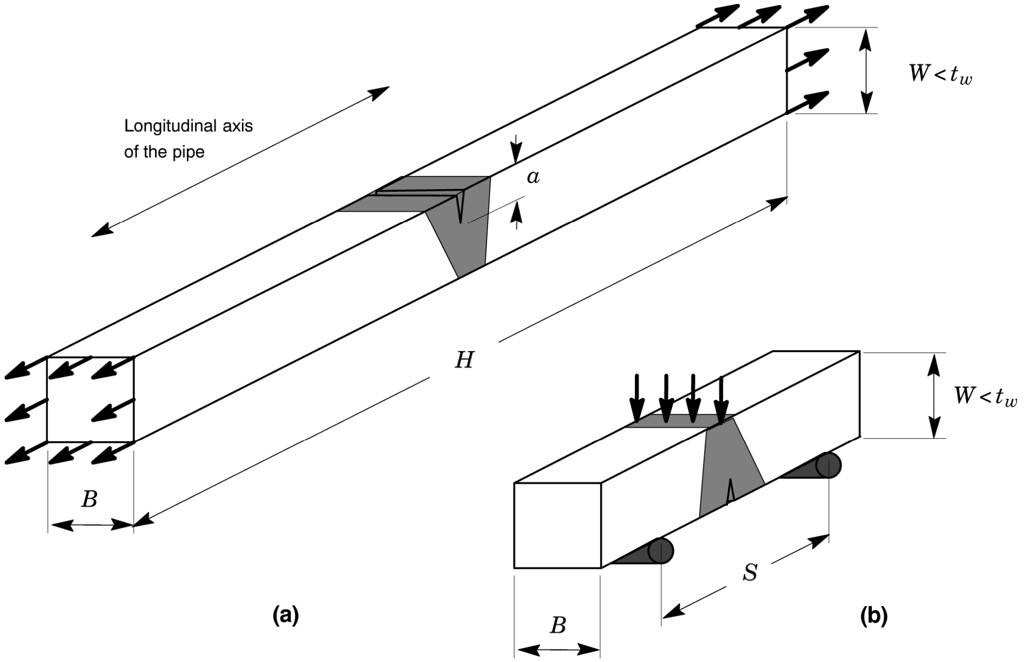


Figure 2.Geometry of tested fracture specimens with weld centerline notch. (a) Clamped SE(T) specimen with *a/W* = 0.4 and *H/W* = 10; (b) 3P SE(B) specimen with *a/W* = 0.25 and *S/W* = 4. All geometries follow (*BxB*) configuration

4. Crack Growth Resistance Curves

This section presents the crack growth resistance evaluated for the tested X80 pipeline girth weld based on laboratory measurements of load and CMOD for the clamped SE(T) specimens and the 3P bend SE(B) specimens with center notched welds. The geometrical features of each specimen type and the considered material properties were presented in the previous section. Figure 3 shows the measured load-displacement curve (*P vs.* CMOD) for both test specimens which clearly reveals the reduced test load for the SE(B) specimen compared with the SE(T) configuration.

Evaluation of the crack growth resistance curve follows from determining J and Δa at each unloading point of the measured load-displacement data. Based upon the previous results for the η-factors and compliance functions provided in previous Section 2, the present analysis employs η_{J-CMOD} and η_{J-LLD} to estimate the plastic component of the *J*-integral, J_p. Figures 4-5 present the measured crack growth resistance curves for the tested clamped SE(T) and 3P SE(B) specimens.

The significant features associated with these plots include: (1) The shallow-crack SE(B) specimen provides *R*-curves which exhibits levels of *J*-values which are comparable to the *J*-values corresponding to the deeply-cracked SE(T) specimen at a fixed amount of crack growth, Δa; (2) The value of the *J*-integral at onset of ductile tearing, J_{Ic}, is fairly independent of specimen geometry and loading mode.

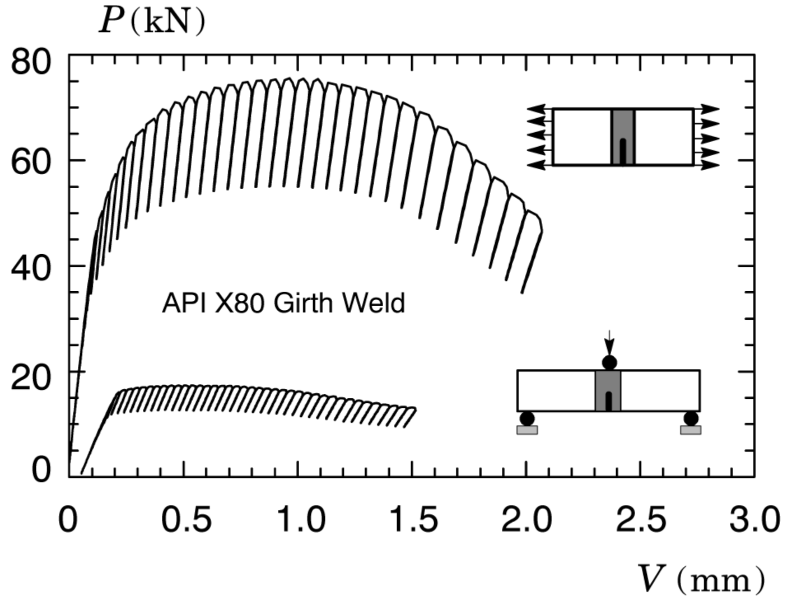


Figure 3. Measured load-CMOD curve for the tested X80 pipeline girth weld using clamped SE(T) specimens with $a/W = 0.4$ and 3P SE(B) specimens with $a/W = 0.25$.

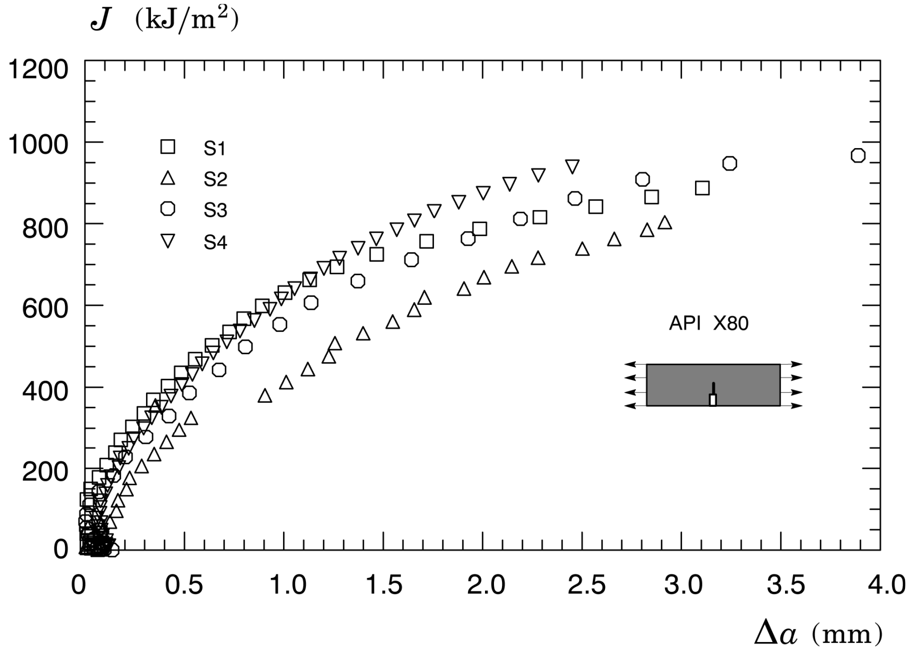


Figure 4. Experimental *R*-curves for tested clamped SE(T) specimens with $a/W = 0.4$

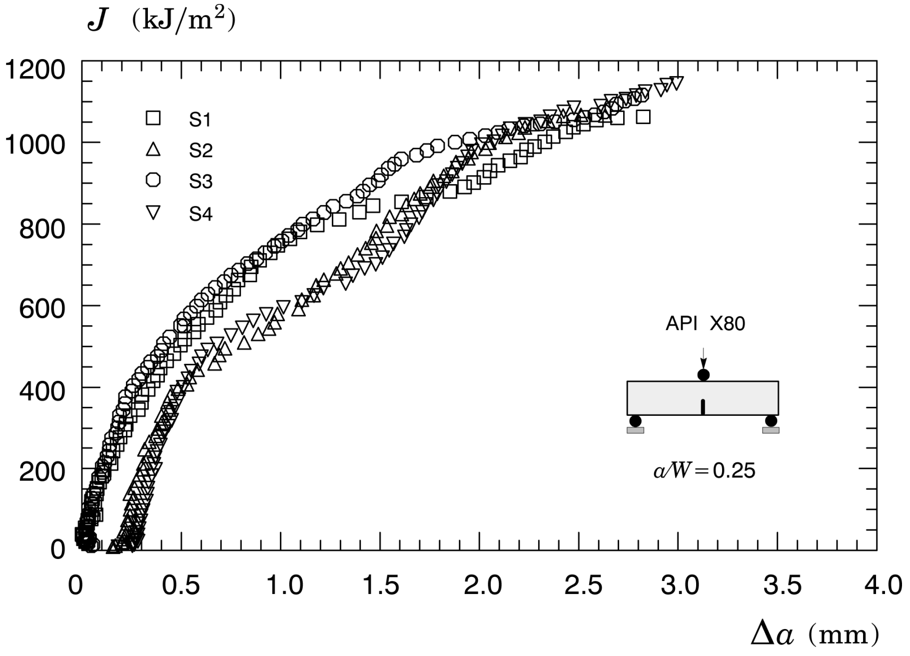


Figure 5. Experimental *R*-curves for tested SE(B) specimen with $a/W = 0.25$.

After testing, all specimens were subjected to heat tinting treatment (300°C for 30 min), and then air cooled before being broken apart. Table 1 shows a comparison of the predicted and estimated crack extension for the tested fracture specimens. For the SE(T) specimens, the deviation ($\Psi = \left|(a_{predicted} - a_{measured})/a_{measured}\right|$) is within 1.5~6.2% while for the SE(B) specimen, the accuracy is within 12~17%%. These results indicate that the UC procedure provides reasonable estimates of the final crack length for the SE(T) specimen. In contrast, crack length estimates for the SE(B) configuration display a somewhat larger deviation compared to the measured crack length; such behavior is mainly due to more severe crack front tunneling that occurred in these specimens.

Table 1. Crack length estimation based on UC procedure.

ID	a_0 (mm)	a_p (mm)		ψ (%)
		Measured	**Predicted**	
SE(B) Specimens				
S1	3.85	7.85	6.68	14.9
S2	4.15	8.21	7.15	12.9
S3	3.65	7.55	6.29	16.7
S4	3.72	7.82	6.53	16.4
SE(T) Specimens				
S1	5.66	8.84	8.76	0.9
S2	6.11	8.06	8.56	6.2
S3	6.29	9.78	9.20	5.9
S4	6.70	10.75	10.59	1.5

5. Concluding Remarks

This work presents an investigation of the ductile tearing properties for a girth weld made of an API 5L X80 pipeline steel using experimentally measured crack growth resistance curves ($J-\Delta a$ curves). Testing of the pipeline girth welds utilized side-grooved, clamped SE (T) specimens and 3P bend SE(B) specimens with a weld centerline notch to determine the crack growth resistance curves based upon the unloading compliance (UC) method using a single specimen technique. This experimental characterization provides additional toughness data which serve to evaluate crack growth resistance properties of pipeline girth welds using SE (T) and SE(B) specimens with weld centerline cracks. Additional work is in progress to further validate the use of shallow-crack SE(B) specimens as an alternative fracture specimen to measure crack growth properties for pipeline girth welds. Ongoing investigation also focuses on establishing robust correlations between *J* and CTOD for stationary and growing cracks in SE(T) and SE(B) fracture specimens.

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