AN ASSESSMENT OF J-R CURVE FROM COMPLIANCE TECHNIQUE IN SE(T) SPECIMENS OF X60 STEEL

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Abstract. *The standard test obtained of the materials J-R curve are made to ensure high constrain conditions, exactly allow toughness conservative values. High pipeline steel press, however, it shows low-constraint because thin wall structure did not supply the strain plane stress. On the other hand, C(T) or SE(B) standard specimens have high-constraint when compared to the non-standard specimens SE(T) or real flawed components with surface cracks usually involve low constraint levels. Therefore, the estimate most suitable of constraint levels at the pipeline will be ensure by SE(B) specimens with shallow crack or single edge notched tension SE(T), allowing results most realistic toughness fracture of structure. In the present work non-standard specimens SE(T) with shallow and deep cracks of API X60 pipeline steel were investigated. J-R curves were obtained by compliance technique (single specimen technique) and used to measuring crack extension performed in shallow and deep cracked nonstandard specimens. The measured crack length was carried out by two the compliance equations developed to the SE(T) specimens and both compared with the multi specimens method. All specimens were fatigue pre-cracked and subsequently side grooved using a Charpy cutter to a total thickness reduction of 20% in an attempt to develop plane strain condition along the crack front. The study shows one the compliance equation for the shallow crack growth condition (a/W=0.2) does not predict the initiation crack growth values when compared to measured values from multiple specimens method. Results from fractographic investigation of CVN-impact and fracture toughness test pieces were observed the presence of single and multiple delamination cavities (splits).*

Keywords*: J-R curve, SE(T) specimen, compliance technique, API X60 steel*

1. INTRODUCTION

Large–diameter, high-pressure gas transmission pipelines have been used more and more widely all over the world. With the development of the pipeline network, safety and maintenance become an important task. The accurate prediction of fracture for oil and gas pipelines with crack-like flaws is essential for fitness-for-service (FFS) methodology, for instance, repair decisions and life-extension procedures and to ensure fail-safe operations which avoid costly leaks and rupture. As defects of various sizes are detected and thinning of pipe walls by aggressive gas gradients is inevitable with time, a better understanding of the fracture toughness and cracking resistance of the pipe materials is required Guo et al (2002). Structural pipeline steels generally exhibit a significant increase in fracture toughness, characterized by the *J-integral*, over the first few millimeters of stable crack extension (Hippert and Ruggieri, 2001). The *J-integral* values have been used extensively as indexes of material toughness for alloy design, material processing, material selection and specification, as well as quality assurance (Zhu and Jang, 2001). The fracture toughness J_{IC} and *J-integral* resistance curves, namely, *J-R* curves have been also used in the integrity assessment of engineering structures with ductile crack tearing or growth. High pipeline steel press, it shows low-constraint because thin wall structure did not supply the strain plane stress. Whereas, the fracture toughness test standard ASTM E1820 was developed only for high constraint specimens, like deep cracked single-edge notched bend SE(B) and compact tension C(T) specimens with the expectation that the results represent lower bound toughness. Accordingly, the application of fracture toughness from high-constraint specimens to low-constraint geometries introduces a degree of conservatism into design (Shu and Leis, 2005). While most of nonstandard specimens (SE(T) or real cracked structures (pipelines) have low crack-tip constraint. As results, the test data of J_{IC} and *J-R* curves are strongly depend on the crack size or crack-tip constraint level Pavankumar et al (2002). Application of the measured fracture toughness to real structures pipeline steels is thus resisted with the justification that the real structure has only shallow cracks and the ASTM fracture toughness measures do not apply (Zhu and Joyce, 2007). As a consequence, the determination of J-R curves for both deep- and shallow-cracked nonstandard specimens SE(T) becomes very important. It is the aim the present study to investigate evaluation of *J-R* curves from standard single-specimen technique using the unloading compliance method for measuring crack extension performed in shallow and deep cracked nonstandard specimens. The measured crack length was carried out by two the compliance equations developed to the SE(T) specimens and both compared with the multi specimens method.

2. EXPERIMENTAL PROCEDURE

The material considered in this investigation was an API 5L-X60 steel, used in oil and gas pipeline. The mechanical tensile test from standard cylindrical was carried out at room temperature following ASTM E8M standard requirements. The experimental results of the mechanical properties from tensile tests were: elastic modulus 207 GPa, 0.2 yield stress 499 MPa, ultimate tensile strength 625 MPa and elongation 21% in the longitudinal (L) direction. Results obtained are in accordance with the requirements prescribed by (API, 2000), this standard defines minimum values for yield strength and ultimate strength of, 448 MPa (65,000 psi) and 552 MPa (80,000 psi) for this steel grade. The chemical composition of this material is presented in Table 1.

Charpy-V notch (CVN) impact specimens were extracted in LT plate orientation. A Wolpert instrument impact testing machine (500 J) has been used for these experiment, following the requirements by (ASTM E23-2000). Test pieces were broken in 5 different temperatures: 25°C, -40°C, -60°C, -80°C and -100°C, and the absorbed energy as a function of testing temperature is shown in Figure 1. At room temperature (25°C) this material presents fully ductile fracture so that transaction effects are not considered in the fracture mechanics testing results.

Table 1. Chemical composition of API 5L-X60 steel (mass. %)

Element	C	Mn	Si	P	S	Cr	Ni	V	Ti	Nb	Al
% weight	0,098	1,63	0,33	0,02	0,02	0,01	0,02	< 0,010	0,022	0,04	0,051

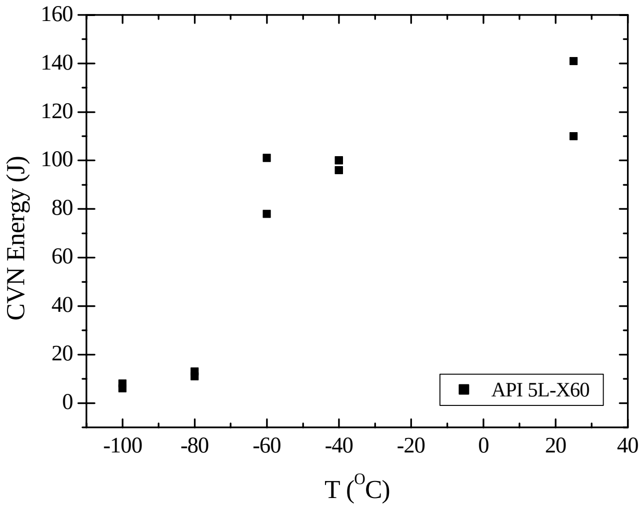

Figure 1. CVN transition curve for API-X60 steel.

2.1 Specimens Geometry

The single edge notched tensions SE(T) specimens were used to measure *J-R* curves. All specimens crack planes were oriented in the LT orientation by ASTM E399. Schematic drawing of this specimen is shown in Fig. 2. The SE(T) specimen has following dimensions: length of reduction section of 156 mm, radius of fillet of 10 mm, overall length of 276 mm, width, W, of 32 mm and thickness of 12.5 mm. This specimen was loaded with a centered pin at center distance of 214 mm. Crack length to width ratios of 0.21 and 0.52 were investigated, corresponding shallow and deep cracks respectively. The specimens were loaded in three-point bending with a span of 128 mm, after precracking by fatigue according to the procedure in (ASTM E1820, 2005). Specimens were side grooved using a Charpy cutter to a total thickness reduction of 20%, in an attempt to develop plane strains conditions along crack front. All specimens were tested at room temperature.

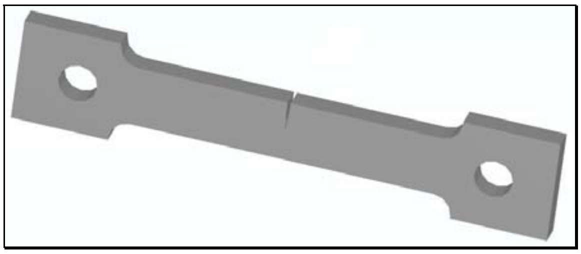

Figure 2. Schematic drawing of specimens SE(T) with crack length to width ratios of 0.21 and 0.52 corresponding shallow and deep cracks respectively.

2.2 Test technique and J-R curves determination

In this investigation the J-R curves of X60 pipeline steel were performed using a single specimen technique, both unloading compliance and multi-specimen tests procedure were carried out which allowed monitoring the specimens crack length. After test, the specimens were heat tinted and then broken in liquid nitrogen. The initial and final crack lengths were measured on the fracture surface by the 9-point technique as described in ASTM E1820. For the SE(T) specimens a standard clip gage was installed to measure the crack mouth opening displacement, CMOD, which was used for crack length estimation, and an LVDT gage was installed on the initial specimen load line to measure the load line extension of the specimen. As the SE(T) specimens, a standardized procedure to calculate the J-resistance is not available, k, η, γ factors used in the Eqs. 1 to 6 for the required elastic and plastic component of the *J* integral were taken from Joyce et al (1993). As also, two rotation corrections were needed, one to correct the COD to obtain the corrected compliance, before of the estimated crack length for the partial unloading. Second correction, was also used to apply a rotation correction to the load line compliance, before calculating the elastic and plastic area components used (Eqs. 1 and 2) to calculate J components. Both procedures were taken from (Joyce and Link, 1995) and were used in according ASTM E1152.

2.3 J integral analysis

The *J* integral was calculated by separating it into elastic and plastic components and calculating the components separately. The elastic J component, J_{el}, is calculated from

$$J_{el} = \frac{k^2}{E'} \quad (1)$$

where K is the elastic stress intensity factor for the specimen, $E' = E/(1-\upsilon^2)$, and E and υ are the elastic modulus and Poisson's ratio, respectively. The plastic component J, J_{pl}, is calculated using the ASTM Standard E1152 equation:

$$J_{pl} = J_{pl(i-1)} + \frac{\eta_i}{b_i}\left[\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \frac{\gamma_i (a_i - a_{(i-1)})}{b_i}\right] \quad (2)$$

A_{pli} = area under the load versus plastic load line displacement curve to increment i,
η_I = the plastic η factor at crack length a_i
b_i = the incremental remaining ligament
W = the specimen width and

$$\eta_i = 5.71(a_i/W) \text{ for } 0 < (a_i/W) \le 0.417 \quad (3)$$

$$\eta_i = 2.38 \text{ for } 0.417 < (a_i/W) \le 1 \quad (4)$$

$$\gamma_i = \eta_i - 1 - (b_i/W)(5.71/\eta_i) \text{ for } 0 < (a_i/W) \le 0.417 \quad (5)$$

$$\gamma_i = 1.38 \text{ for } 0.417 < (a_i/W) \le 1 \quad (6)$$

Formulas for the compliance relationships, K's, η's, γ's used to obtain the J-R curves for the SE(T) specimen are in according Joyce et al (1993).

2.4 Crack extension measurements

The fracture toughness test standard ASTM E 1820-05 is designed for the *J* determination using the unloading compliance method to standard specimens for crack extension measure. However, the SE(T) specimens are categorized as nonstandard one, to which the E1820 may not be applicable. For this reason, it is necessary to apply in the elastic compliance method an adjustment compliance equation to obtain measure crack length or incremental crack to the SE(T) specimens. In the present study, compliance equation to the SE(T) specimens used are according Joyce et al (1993) and (Cravero and Ruggieri, 2007), both developed compliance equation used to the SE(T) specimens (pin-loaded) with initial crack length *a* varied producing various ratios of *a*/W 0.35 to 0.65 and *a*/W 0.1 to 0.7, respectively, as following:

$$a/W = 1.012525 - 2.95323u' + 6.68u'^2 - 17.1954u'^3 + 25.3571u'^4 - 12.9747u'^5 \quad (7)$$

$$, a/W = 1.0056 - 2.8744u' + 5.4420u'^2 - 12.510u'^3 + 16.102u'^4 - 7.0642u'^5 \quad (8)$$

$$u' = \frac{1}{1+\sqrt{\dfrac{E'B_e\delta}{P}}} \quad (9)$$

For side-grooved specimens, the thickness *B* is replaced by B_e namely, $B_e = B-(B-B_N)^2/B$, where B_N is the net specimen thickness at the side groove roots.

3 Results and discussion

Results from fractographic investigation of CVN-impact and fracture toughness test pieces were observed the presence of single and multiple delamination cavities (splits) as can be drawn in Fig. 3. In this API 5L steel, delamination is believed to occur due to decohesion of ferrite-pearlite interface (Shanmugan and Pathak, 1996). As the out-of-plane constraint is highest at the centre of the specimen, the delamination in the middle part of all are most severe. Reported experimental data by Guo et al (2002) indicated large delaminations start from the initial crack front and growth with crack extension to the final fracture point. Same characteristic occurred here, as shown clearly in Fig. 4. Secondary delaminations are concentrated at the 1/4 thickness points from the free surfaces and similar to the main delamination. The main delamination at the centre of specimen releases the out-of-plane constraint completely on the middle plane Guo et al (2002).

Figure 3. Typical fracture surface of shallow-cracked SE(T) specimens with multiple delaminations.

The fracture surface profile is predominantly flat along the whole ligament length on a macroscopic point of view as shown by Fig. 3. Beside the delamination, a classical profile with dimples was observed in the SEM. Therefore, the phenomenon responsible for crack initiation and growth is void growth and coalescence internal to the specimens.

Figure 4. Typical fracture surface of shallow-cracked SE(T) specimen with main and secondary delaminations.

Figs. 5 and 6 illustrate a comparison of load versus crack extension curves between both elastic unloading compliance and multiple specimens methods to the measure crack length for shallow (using Eqs.7 and 8) and deep (only Eq.7) cracked SE(T) specimens, respectively. It is possible to observe in Fig.5, the compliance equation (Eq. 7) used from Joyce et al (1993) does not predict the initiation crack growth values when compared to measured values from multiple specimens method, to large remaining crack ligament, this is, shallow ductile crack growth. Whereas, the compliance equation (Eq. 8), the measured crack extension values are more consistency in relation to multiple specimens method. In recent work (Cravero and Ruggieri, 2007) investigated that during procedure to correction the COD to obtain the corrected compliance, before of the estimated crack length for the partial unloading, the accurate choice for the position of the center of rotation, Rc, it is great importance. Because Rc depends strongly on hardening properties and deformation level mainly for shallow cracked SE(T) specimens. The authors expressed by the sum of crack length and a fraction of the remaining crack ligament in the form $Rc = a + r_p(W - a)$ where r_p denotes the plastic rotation factor, (was adopted r_p= 0.9), which r_p-factor depends rather strongly on strain hardening for the shallow cracked SE(T) specimen.

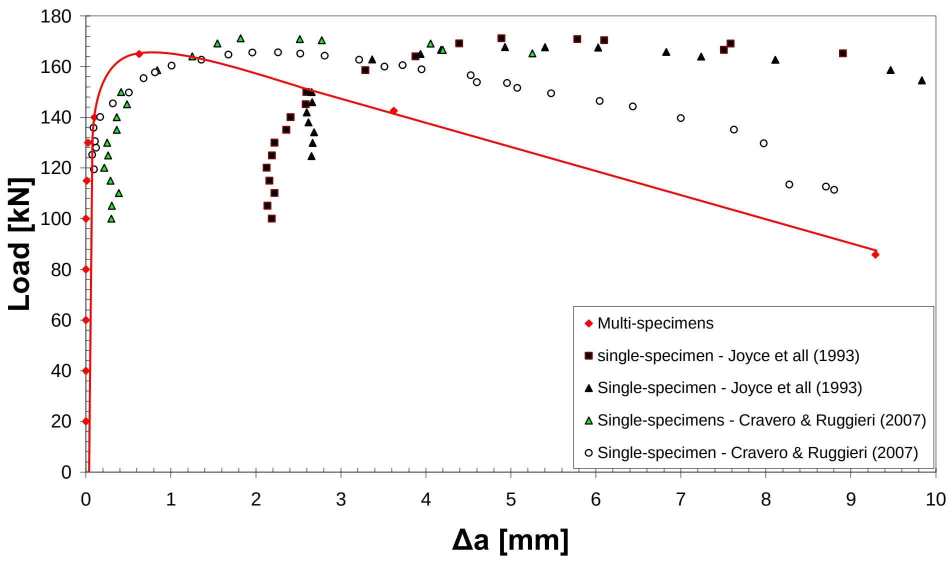

Figure 5. Comparison of load versus crack extension curves between both elastic unloading compliance and multiple specimens methods to the measure crack length for shallow (using Eqs.7 and 8) cracked SE(T) specimens.

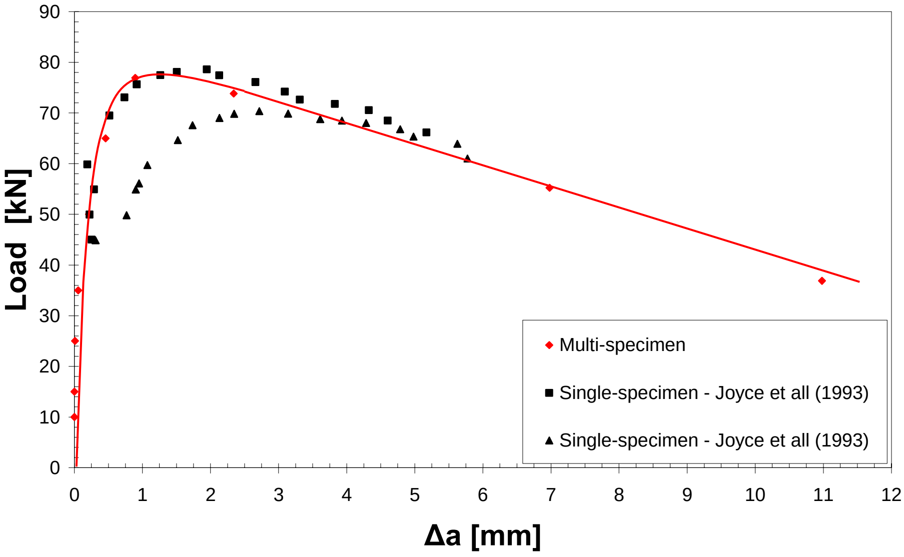

Figure 6. Comparison of load versus crack extension curves between both elastic unloading compliance and multiple specimens methods to the measure crack length for deep (using Eq.7) cracked SE(T) specimens.

This anomaly, that it can be drawn in Fig. 5, using Eq. 7, is attributed the choice of the position of the center of rotation, Rc. In this case, Joyce et al assume that position for the center of rotation for the SE(T) specimen is $Rc = (a+W)/2$, and they do not consider the r_p-factor for both shallow and deep cracked specimens. Nevertheless, as Rc is less affected by hardening and deformation level for deep cracked SE(T) specimens, namely, the r_p-factor is practically independent of strain hardening for the deep cracked SE(T) specimens (Cravero and Ruggieri, 2007). Accordingly, the measured crack length values using Eq. 7, for the deep cracked SE(T) specimens were equivalent to the multi specimens method, as can be drawn in Fig. 6.

Figs. 7 and 8 display the experimental crack growth resistance curve from Eqs. 1- 6. For the shallow crack specimens (Fig. 7), the measured crack length values were used from compliance equation Eq. 8. It is possible to notice in Fig. 7, the features of ductile tearing behavior along crack growth resistance curve, as also, an elevated fracture toughness behavior in comparaison with the deep-cracked specimens (Fig.8). Both features are observed at crack initiation and throughout the ductile crak growth region. Such behavior is entirely consitent with previous results obtained by (Joyce et al, 1993) and (Shu and Leis, 2005). However, the magnitude of the thoughness values found here, mainly for the shallow cracked condition, have been superestimated. It was attributed to use an LVDT gage during the tests, recorded load-line displacement (LLD) of the specime no more closely of the crack mouth opening.

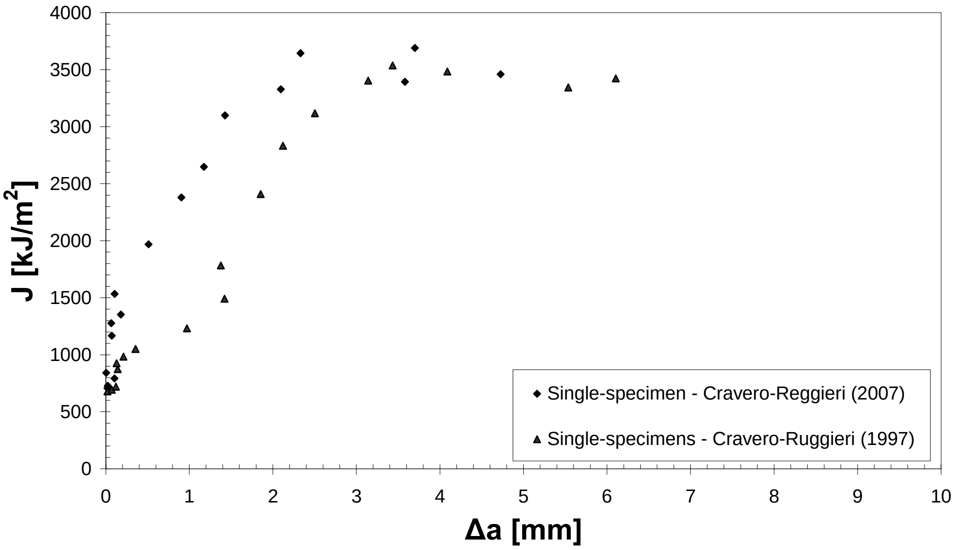

Figure 7. Experimental *J-R* curves for shallow crack SE(T) specimens with measured crack length values from compliance equation Eq. 8.

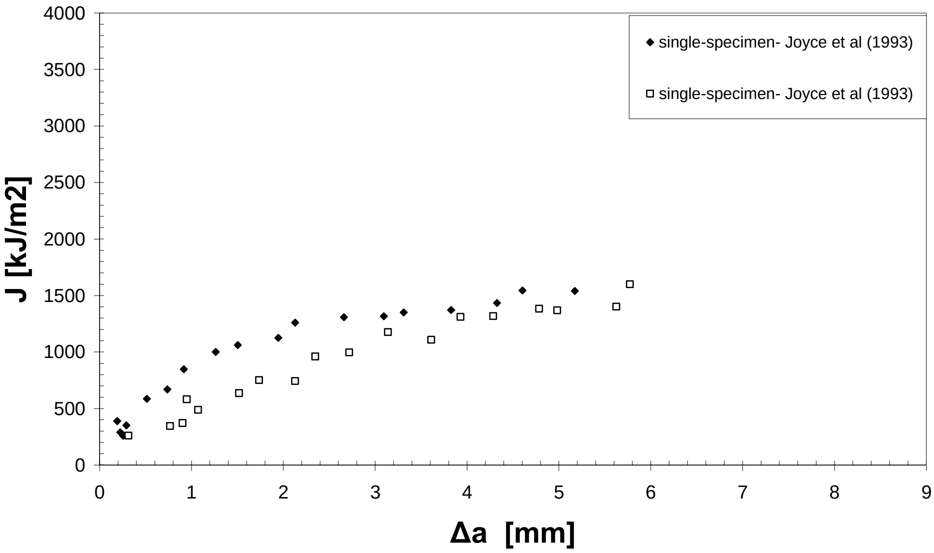

Figure 8. Experimental J-R curves for deep cracked SE(T) specimens with measured crack length values from compliance equation Eq. 7.

The average predicted a_f values is 14.57 mm which it is very agreement with the measured value of 15,08 mm for the final crack length, corresponding a difference between the predicted an the measured of 3.5%.

4 CONCLUDING REMARKS

The present study investigated evaluation of *J-R* curves in SE(T) specimens of X60 steel from standard single-specimen technique using the unloading compliance method for measuring crack extension performed shallow and deep cracked nonstandard specimens. The measured crack length was carried out by two the compliance equations developed to the SE(T) specimens and both compared with the multi specimens method. The results obtained can be summarized as follows: The compliance equation developed by Cravero-Ruggieri, showed be more accurate and convenient to determine the crack extension values for the shallow cracked nonstandard specimens SE(T) when compared to the compliance equation obtained by Joyce et al. This suggest, with use to Eq. 8, it may contribute to support developments of standard test procedures from the nonstandard specimens SE(T) to application in measurements of crack growth resistance for pipelines. On the other hand, for the deep cracked condition, both the compliance equations have been produced equivalent crack extension values.

It was observed single and multiple delaminations (split) at fracture surface from the shallow and deep cracked specimens. This suggest, the delamination decreases the constraint, thus increasing the compliance of the specimens, accordingly, it can affects the fracture toughness values along of resistance curve.

5. ACKNOWLEDGEMENTS

This work is supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) through Grant 04/02856-0. Authors also acknowledge the Brazilian State Oil Company (Petrobrás) for making available the SE(T) fracture specimens used in testing of the API 5L X60 pipeline plate.

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