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# FRACTURE TOUGHNESS EVALUATION OF FRICTION STIR WELDED API 5L X-80 STEEL PLATES

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## Abstract

The solid state joining process known as friction stir welding (FSW) offers several advantages over the conventional fusion welding process. Such advantages are widely recognized and have made possible the penetration of this technology mainly on the transportation industry, where the use of light materials is important. Thus, FSW of Al alloys is a mature and now well established technology. On the other hand, the use of FSW to join high temperature melting alloys, such as steels is still an emerging technology, where important challenges are still being faced by welding and materials scientists and engineers. However, the advantages associated to the use of FSW to join steels, such us the high productivity, inherent automation, produced forged-like microstructure and the consequently improved mechanical properties as well as the avoidance of hydrogen induced cracking are driving intense research in this area. Nevertheless, fracture toughness data is scarce in the open literature and there are important differences on the results reported by several groups due to the differences on the process parameters used. In the present study, 12 mm thick API 5L X80 steel plates were used to produce FSW butt joints. The two passes (on both sides of the plates) welds were submitted to Critical Crack Tip Opening Displacement ($CTOD_{eot}$) testing at 25, -15 and -35 °C. PCBN-WRe tools with threaded conical shape, 6 mm long pin and convex threaded shoulder were used at travel and rotation speeds of 100 mm/min and 300 RPM, respectively. The welding direction was perpendicular to the plates rolling direction. The notches were located at different regions of the joints such as, center of the stir zone (SZ), at the advancing (HAZ/AS) and retreating (HAZ/RS) sides of the heat affected zone. Optical and scanning electron microscopy were used to evaluate the microstructure and fracture surfaces. Delaminations (brittle crack extension) were regularly observed on the base material, were not as common and smaller on the HAZ specimens, and were not observed on the SZ samples. The $CTOD_{eot}$ values did not vary too much for all the temperatures and regions evaluated. The SZ presented a slight tendency towards lower fracture toughness at the lower temperatures. However, the evaluated FSW joints showed fracture toughness values in accordance to the DNV OS F101 (2010) standard for offshore structures for oil and gas.

## 1. Introduction

The X80 API 5L is a high-strength low-alloy steel (HSLA), which chemical composition and processing parameters are carefully designed to provide very good toughness (Ju et al. 2007). Such steels are widely used for oil & gas industry for pipelines construction. As part of the pipeline construction such alloys are submitted to arc welding, which provides the required mechanical performance. Arc welding of pipeline steels for field joining of 12 m long pipes is a mature and well established technology. A variety of processes ranging from SMAW to automated GTAW, GMAW (Miranda et al. 2009), SAW (Castelluccio et al. 2013) and FCAW are widely used within the industry. However,

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seeking productivity improvements, further and more reliable automation for arc welding and even hybrid laser-GMAW (Caccese et al. 2006) processes are under development for such field applications. Therefore, there is interest within the oil and gas industry for new technologies. FSW of steels could offer advantages compared to the conventional fusion welding (Santos et al., 2013). Kumar et al. (2010) demonstrated the feasibility to weld 19 mm thick API 5L steels using two FSW passes. They found acceptable $CTOD_{eot}$ values within the SZ, however, lower than the base material and slightly higher than the minimum required by the standards. Santos et al. (2010) used FSW to join 12 mm thick X80 API 5L steel. They evaluated the joints CTOD at room temperature. In such study process parameters that produced sound welds with elevated fracture toughness values at the SZ and HAZ were developed. In the present study was given continuity to Santos et al. (2010) work, studying the toughness behavior of coincident advancing side 2 passes joints. The $CTOD_{eot}$ values were determined at 25, -15 and -35 °C within the SZ, and advancing side (HAZ/AS) and retreating side (HAZ/RS) HAZ.

## 2. Experimental Procedures

### 2.1 Materials

Plates of X80 API-5L steel 100x400x12 mm were used to produce butt FSW joints. Both chemical composition and mechanical properties presented at Table 1 and 2 were provided by a Brazilian steel producer. No bevel preparation was made on the plates, just as machined straight edges were used.

Table 1. Chemical composition [Wt %], X80 API 5L Steel

| C | Si | Mn | Cu | Cr | Al | Mo | Nb | Ni | P | Ti | V | N* | B* | S* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,07 | 0,25 | 1,79 | 0,02 | 0,14 | 0,03 | 0,19 | 0,07 | 0,02 | 0,01 | 0,01 | 0,03 | 50 | 2 | 13 |

*ppm

Table 2. Mechanical properties of X80 API 5L steel.

| Property | MPa | Ksi |
|---|---|---|
| Yield strength (YS) | 531 | 77 |
| Tensile strength (TS) | 710 | 103 |
| YS/TS (%) | 75 | |
| Average hardness (HV0.2) by microindentation | 235 HV | |

### 2.2 Welding

In accordance with the previous study by Santos et al. (2010) friction stir welds were produced using the same welding parameters. Travel and spindle speeds of 100 mm/min and 300 RPM, respectively, were applied. A metallic WRe matrix (25%Re) composite material reinforced with 60%vol CBN (Cubic Boron Nitride) tool with 6 mm long threaded conical pin and convex threaded shoulder was used. The joints were performed on force control mode at 28 kN axial force using a dedicated FSW machine. The welding direction was perpendicular to the plates rolling direction as schematically presented in the CTOD sample drawing shown in Figure 1. These 12 mm thick plates were welded using two passes with approximately 6 mm penetration from both sides of the plates. The two passes were made for the advancing sides of both welds to coincide. The advancing side has been shown to be the critical point region for defect formation and the fracture toughness during FSW. Thus these coincident advancing side joints represent the worst case scenario for the fracture toughness determination.

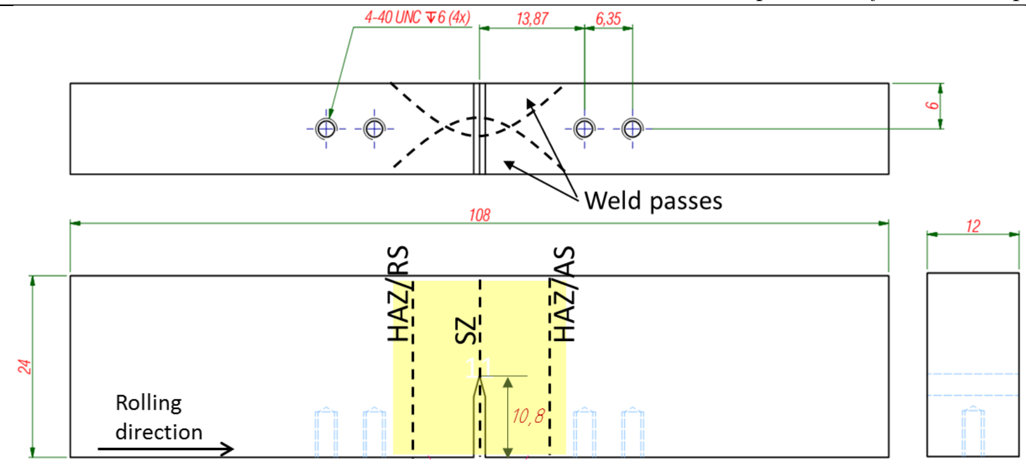



Figure 1. Schematic representation of FSW CTOD single edge notched bend (SENB) specimen with notch located at the stir zone. Notice the plates rolling direction. Dimensions in mm.

**2.3 Tests**

The fracture toughness was assessed with $CTOD_{eot}$ parameters according to the ASTM E 1290-08 (2010) standard. The three-point bending specimen (SENB) was selected. A fatigue pre-crack length-to-width ratio ($a_0$/W) of approximately 0,6 was used. The span length (S) between the support rollers was of 96 mm. The specimen dimensions are presented in the Figure 1. The notches in the CTOD specimens were oriented along the through-thickness (L–T) direction. There were three different notch locations: advancing side heat affected zone (HAZ/AS), retreating side heat affected zone (HAZ/RS), and stir zone (SZ), as shown in Figure 2. As can be seen in this figure, the HAZ notches and therefore the cracks in these samples actually propagate along a mixture of base material in the center, HAZ across most of the fracture surface, and a bit of stir zone on the sample edges. However, it is not possible to produce a K type welded joint using FSW, and therefore, this regions mixture is unavoidable in large fracture toughness samples.

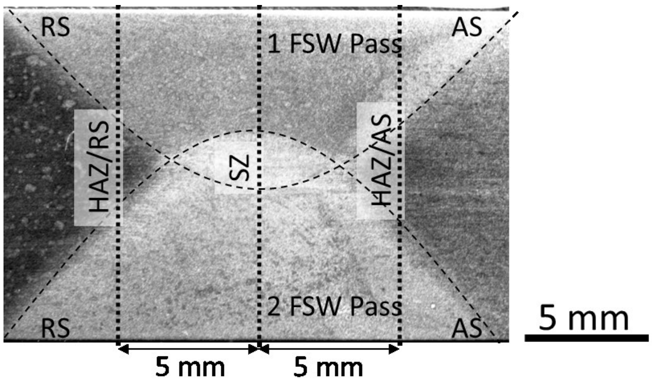



Figure 2. Joint cross section macrograph with the schematic representation of FSW passes and CTOD specimens notches positions.

## 3. RESULTS AND DISCUSSION

### 3.1 CTOD

Figure 3 presents the $CTOD_{eot}$ values. As can be seen in this figure, the largest data dispersion on the $CTOD_{eot}$ values was found for the base material. This data scattering is due to the delamination appearance during the early stages of the tests. This delamination behavior has been also reported by Joo et al. (2012) for HSLA steels during Charpy tests. He proposed that such delamination took place due to the material banding and hot rolling texture. This explanation is supported by others authors like Silva (2004) and Hippert (2004). The delamination occurrence was most common near the plate segregated region at the mid thickness of the base material plates. Smaller delaminations were found on the

HAZ/AS and HAZ/RS CTOD samples tested at different temperatures. Such delaminations were located close to the center of HAZ CTOD samples, where unprocessed base material is present, as shown in Figure 2.

Santos et al. (2010) found Martensite-Austenite constituent (MA) within the joint SZ. These hard MA blocks may induce a brittle behavior, especially if they present an elongated morphology, as described by Lan et al. (2011). The MA constituent may be related with the SZ decreasing $CTOD_{eot}$ values with lower test temperatures. As shows in the Figure 3, the $CTOD_{eot}$ data scattering differences between the HAZ/AS and HAZ/RS could be related with the more relevant microstructural inhomogeneities expected and observed at the HAZ/AS. In addition, the joint advancing side is regularly the hardest region, as reported by Kumar et al. (2010) and Santos et al. (2010). Nevertheless, all $CTOD_{eot}$ values here reported qualify the welded joints for commercial pipeline applications according to the DNV OS F101 (2010) standard.

It should be pointed that the curved crack front are not fully in agreement to ASTM standards, but these results exposed the actual welded joint behavior. The fracture surfaces exhibit a curved fatigue crack, which was more severe in the welded samples than the BM, as shows in Figure 4.a and 4.b. The BM behavior was reported by Hermenegildo (2012). In addition there is a difference in the stress state and ductility between the base material and the welded material. The higher ductility of the HAZ and SZ was made evident by the fatigue crack growth conditions and the dimple size observed on the fracture surfaces.

The fractographic analysis of the BM samples revealed a mixture of dimples and cleavage morphologies, as shown in the Figure 4.c and d. The microestrutural constituents and grain size in the welded material and affected regions play an important role in fracture toughness response. As shown in Figure 4.c, a ductile fracture surface formed by dimples was found in almost all the evaluated conditions, a result similar to that of Santos et al. (2010). In the weld regions the fracture surface shows a predominantly ductile behavior, despite the small differences in the $CTOD_{eot}$ values and dimple size among the different weld regions, as shown in Figure 4.d-g.

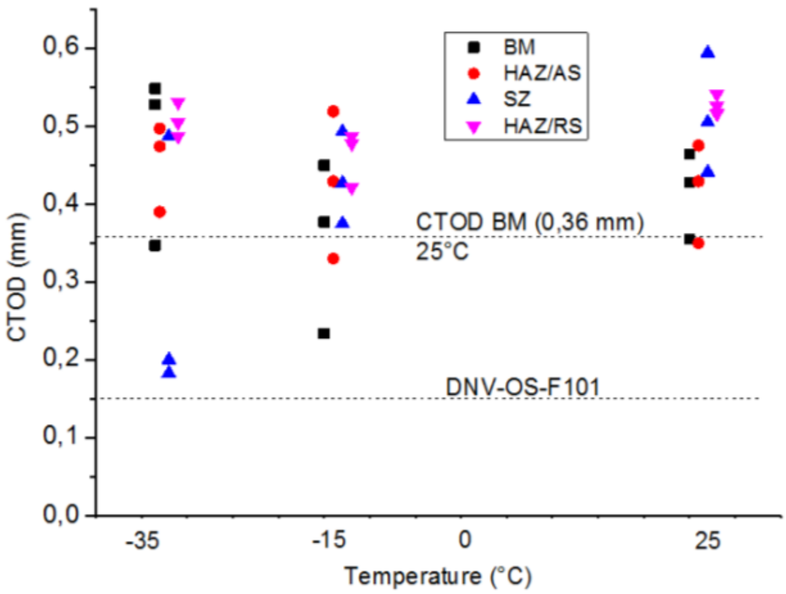
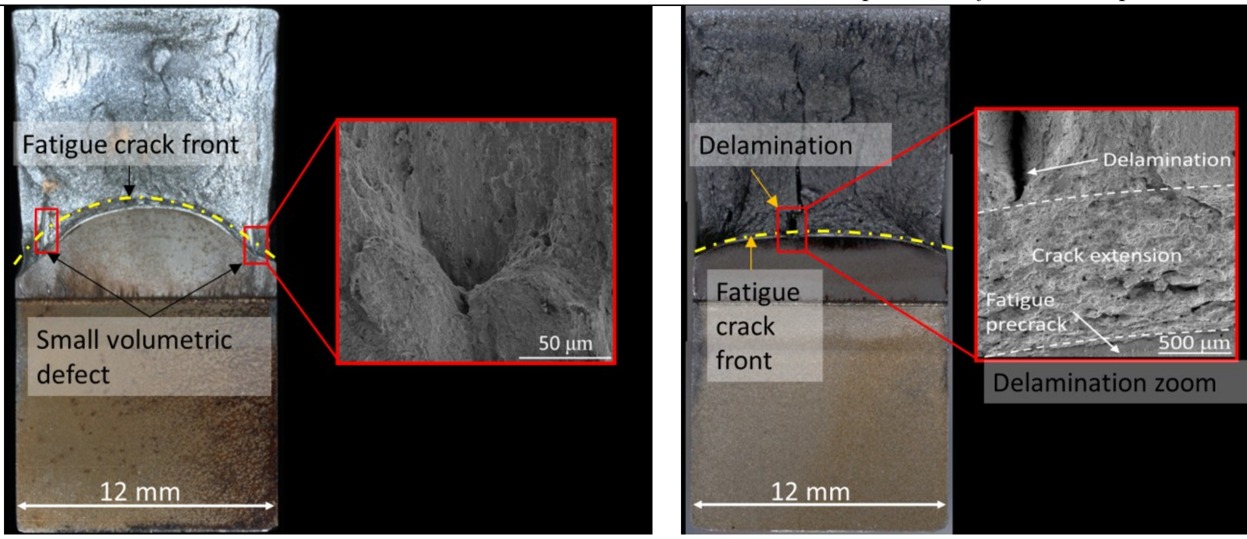
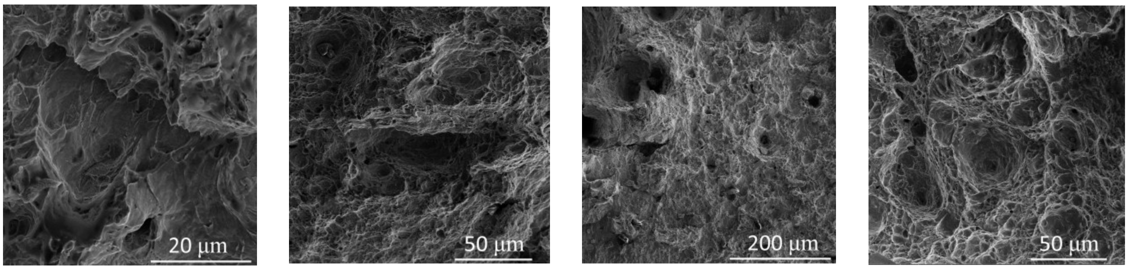



Figure 3. $CTOD_{eot}$ values for the different FSW regions. BM: Base Material. HAZ/AS: advancing side heat-affected zone, HAZ/RS: retreating side heat-affected zone, and SZ: Stir Zone

Some welded specimens showed very small volumetric defect located at the upper region of the SZ/HAZ interface, as shown in the Figure 4.a. these defects were observed in some CTOD samples extracted near to the final part of the joint. The defects could be related with the insufficient plasticization of the material during the welding process, as proposed by Adamowsk et al. (2007). Figure 4.a and b show a fracture surface of a specimen tested on 25 °C which corresponds to the lowest CTOD value in Figure 3.




a) b)




d) e) f) g)

Figure 4. CTOD samples fracture surfaces. a) Weld defect at the advancing side interface has been revealed on the sample tested at 25°C; b) BM fracture surface showing delamination. Stable crack growth region: d) BM; e) SZ; f) HAZ/AS; and h) HAZ/RS.

## 5. Conclusions

This paper presents the $CTOD_{eot}$ values of 12 mm thick API 5L X80 steel plates welded by FSW. The joints were completed by two welding passes with coincident advancing sides. The fracture toughness was evaluated at base material (BM) and three different regions of the joint: advancing side heat affect zone (HAZ/AS), retreating side heat affect zone (HAZ/RS), and stir zone (SZ).

All $CTOD_{eot}$ values qualify the welded joints fracture toughness for eventual commercial offshore pipeline applications according with the DNV OS F101 (2010) standard. On the other hand the crack front did not comply with the ASTM standard. However, the presented results represent the actual joint material behavior. The measured $CTOD_{eot}$ values have shown small variation across the whole tested regions and temperatures. Nevertheless, the BM and HAZ/AS presented more scattered results and the SZ presented a slight tendency to lower fracture toughness with the test temperature reduction.

All the BM CTOD specimens presented delaminations due to unstable brittle crack extension.

Some weld small volumetric welding defects and microstructural inhomogeneities were found on the advancing side, where also was observed the higher $CTOD_{eot}$ values scattering. The more microstructuraly homogeneous HAZ/RS consequently presented the lower spread in the $CTOD_{eot}$ values.

High tunneling was observed during the fatigue crack growth in the HAZ and SZ specimens due to uneven microstructure, especially in the HAZ.

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