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# Fracture toughness assessment at different temperatures and regions within a friction stirred API 5L X80 steel welded plates

Julián A. Ávila [a,d], Cassius O.F.T. Ruchert [b], Paulo Roberto Mei [a], Ricardo R. Marinho [c], Marcelo T.P. Paes [c], Antonio J. Ramirez [a,d,e,*]

[a] School of Mechanical Engineering, University of Campinas, Rua Mendeleyev 200, Campinas, SP 13083-860, Brazil
[b] Engineering School of São Carlos, University of Sao Paulo, Av. Trabalhador São Carlense 400, Sao Carlos, SP 13566590, Brazil
[c] Petrobras, CENPES, Av. Horácio Macedo 950, Rio de Janeiro, RJ 21941-915, Brazil
[d] Brazilian Nanotechnology National Laboratory, Rua Giuseppe Máximo Scolfaro 10000, Campinas, SP 13083-970, Brazil
[e] The Ohio State University, 1248 Arthur E. Adams Drive, Columbus, OH 43221, USA

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ABSTRACT

Friction stir welding (FSW) is a promising candidate for use in pipeline steels because it offers high productivity and sound welded joints. This study presents a fracture toughness assessment of FSW-welded two-pass butt joints, different regions within the joints and tests temperatures (25 °C, −15 °C, −20 °C, −35 °C, −40 °C) were used. Base plates of API-X80 steel 12 mm thick were FSW-welded using two different pass sequences, coincident and alternate directions. The results presented consistently high toughness values down to −20 °C for all the assessed notches, which indicates that FSW may be suitable for general pipelines steels applications in that range of temperatures.


## 1. Introduction

Friction stir welding (FSW) presents some advantages regarding productivity and quality of welds in pipeline steels compared to conventional fusion welding, *e.g.* the demonstrated possibility to weld 19 mm thick API 5L steels using two passes [1]. Even though the Welding Institute developed FSW more than 20 years ago, the adoption of the practice in steels has yet to be fully accepted. The reason in part is the elevated cost of the required welding equipment and tools needed to join steels and other high temperature alloys, which has hindered further research and development in this field.

Kumar et al. [1] reported crack tip opening displacement (CTOD) values under 0.1 mm at 20 °C and 0 °C for two different FSW welded joints of X80 steel. Also, low fracture toughness in welds made with a W-Re tools and welding speeds ranging from 180 to 250 mm min$^{-1}$ were reported [2]. It has also been pointed out that the stirred zone (SZ) in API steels FSW joints exhibits characteristics similar to the coarse-grained heat affected zone in arc welds [2], which could, at least, partially explain the low toughness reported for some of these FSW joints. On the other hand, excellent toughness behavior at room temperature for FSW joints of API steels has been reported [3]. However, some of these technical publications do not report or adequately emphasize all the parameters used, which could be misleading or make it difficult to determine relevant results. Therefore, these apparently contradictory results bring to light the fact that the microstructure and mechanical

* Corresponding author at: 1248 Arthur E. Adams Drive, Columbus, OH 43221, USA. Tel.: +1 (614)292 8662.
*E-mail address:* ramirezlondono.1@osu.edu (A.J. Ramirez).

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**Nomenclature**

| | |
|---|---|
| $a_0/W$ | crack-length-to-width ratio (mm/mm) |
| AAS | alternate advancing sides joint |
| AS | advancing side of the FSW joint |
| B | specimen thickness (mm) |
| CAS | coincident advancing sides joint |
| $CE_{Pcm}$ | carbon equivalent accordingly to the API-5L/ISO-3183 (2007) standard |
| CTOD | crack opening displacement (mm) |
| *d* | represents values that presented severe delamination |
| DT-SCG | ductile tearing from the stable crack growth |
| F | factor to determine the acceptance or rejection of the pop-in at ASTM E1820-13 standard |
| FC | fatigue crack |
| FF | final crack fracture |
| FSW | friction stir welding |
| HAZ | heat affected zone |
| HAZ-1 | Notch locations at the HAZ through-thickness over the advancing side of the first pass |
| HAZ-2 | Notch locations at the HAZ through-thickness over the retreating side of the first pass |
| HSLA | high strength low alloy |
| HT-HAZ-I | high temperature heat affected zone |
| HZ | hard zone |
| IT-HAZ | intermediate HAZ |
| J3 | FSW-welded joint identified as J3 |
| LT-HAZ | low temperature HAZ |
| M–A | martensite–austenite microconstituent |
| PCBN–WRe | polycrystalline cubic boron nitride and tungsten rhenium |
| RS | retreating side of the FSW joint |
| RSZ | restirred zone |
| SCG | stable crack growth |
| SE(B) | single-edge notched bend specimen |
| SZ | stirred zone |
| SZ-G | general stirred zone |
| SZ-HT-HAZ | SZ affected by the HT-HAZ of the second pass |
| SZ-IT-HAZ | SZ of the first pass affected by the IT-HAZ of the second pass |
| SZ-SCG | stretch zone from the stable crack growth |
| $\odot$ | Indicates weld direction out of the page |
| $\otimes$ | Indicates weld direction into the page |

performance of such FSW joints are highly dependent on the materials being welded, tool material and welding parameters being used. This also confirms the necessity of new and more comprehensive studies in this field.

In the present study, optimized welding parameters were used to produce two-pass FSW joints in 12 mm thick plates. The fracture toughness was addressed through CTOD testing, tests were conducted at temperatures of 25, −15, −20, −35 and −40 °C, with notches placed in different regions within the welded joints. The fracture toughness data has been analyzed with the support of microstructural and fractographic examinations, allowing conclusions to be drawn regarding the potential safe application areas for FSW of HSLA steels.

## 2. Experimental procedures

### 2.1. Materials

The X80 API-5L steel plates used for this study were fabricated using thermomechanical control process. The carbon and sulfur were analyzed separately with a dedicated fusion–combustion analyzer, while the other chemical elements were determined by using an arc spark optical emission spectroscopy. The measured chemical composition is shown in Table 1.

**Table 1**
Chemical composition of the API 5L X80 steel in wt.%, ppm (indicated by *) and carbon equivalent is represented by $CE_{Pcm}$ [4].

| C | Si | Mn | Cu | Cr | Al* | Mo | Nb | Ni | P* | Ti | V | N* | B* | S* | $CE_{Pcm}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 0.22 | 2.07 | 0.01 | 0.15 | 0.03 | 0.18 | 0.07 | 0.01 | <60 | 0.01 | 0.03 | 0.02 | <5.00 | 22 | 0.22 |