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Friction stir welding of steels for the oil and gas industry

A J Ramirez[1-2], T F C Hermenegildo[1-2], V F Pereira[1], J A Avila[1-2], T F A Santos[1-2], P R Mei[2], L P Carvalho[3], R R Marinho[3], M T P Paes[3]

[1] Brazilian Nanotechnology National Laboratory (LNNano), Brazil
[2] School of Mechanical Engineering, University of Campinas, Brazil
[3] Petrobras S.A., Brazil

Abstract

Friction stir welding (FSW) has become a viable and important manufacturing alternative in several industries. This solid-state welding process offers considerable improvements in the mechanical properties of the joint. At the beginning it was developed as a joining alternative for light Al and Mg alloys and it eventually evolved to higher melting temperature alloys, such as steels, stainless steels, titanium alloys and Ni-based alloys. Most of these alloy systems are widely used in the oil and gas industry, where dissimilar joining among them is not uncommon. Conventional arc welding processes and more recently hybrid combinations with laser welding are widespread or under development to be used in these industries. However, metallurgical issues associated with the solidification process and hydrogen embrittlement impair the weldability of most of these high melting temperature alloys. Therefore, FSW is an interesting alternative to overcome some of the challenges associated with the similar and dissimilar joining of structural steels, stainless steels, and Ni-based alloys, especially for circumferential joining of pipelines. Recent developments on weldability studies of pipeline steels seeking the technology deployment will be presented ranging from parameters development, microstructural characterization, and fracture toughness to process robustness evaluation.

Keywords: FSW, Steel, API-Steel, CTOD

1. Introduction

Friction stir welding (FSW) of light Al and Mg alloys development started on 1991 at The Welding Institute, by a group leaded by W. Thomas [1)] and is now a well established technology with important applications on the aerospace and transportation industries [2, 3)]. It did not take long before several researchers began studies on FSW of steel and other medium and high meting temperature alloys, as Cu alloys, stainless steels, Ni-based alloys, and Ti Alloys. From the very beginning, joining and processing such materials revealed to be a very challenging task, especially because of the elevated temperatures and forces associated to the process. Nevertheless, the motivation for such endeavor has been driven by several of the advantages generally attributed to FSW as:

- Very good mechanical performance of the joints due to the forged-like microstructure;
- Expected low susceptibility to Hydrogen embrittlement;
- Low distortion and residual stresses;
- Superior reproducibility and robustness with low defect formation rate;
- Cost and time efficiency;
- Inherent automation;
- Suitability for hostile environments;
- Joining of conventionally un-weldable materials;
- Joining of dissimilar materials;
- Safe for the welding operator due to inexistence of toxic fumes;
- New opportunities for novel and unique applications.

For the oil and gas industry, the possibility to produce highly reliable joints involving difficult to weld materials, as high strength steels or even joints involving dissimilar materials, in addition to the possibility to expedite and simplify factory and field joining have been the main driving force for to push FSW of high melting temperature alloys development, as shown in Table 1. However, there are challenges ahead before, such technology is embraced by the contractors and massively deployed within the oil and gas industry. Among these challenges, some deserve special attention:

- Process Development;
    - o Limited industrial equipment availability;
    - o Tool materials to withstand the process conditions, especially for elevated thickness;
    - o Tools availability;
    - o Limited knowledge on tool design and parameters optimization;
    - o Inspection techniques and methodologies need to be readdressed to comply with FSW;
- Base materials have not been developed with FSW in mind;
- Very limited knowledge available regarding the material microstructural evolution associated to the process and the joints performance;
- Limited availability of engineers and technicians with knowledge on this technology;
- Specifications and codes applicable to specific industries are almost inexistent;
- Thoroughly cost efficiency evaluation;
- Development of trust within the community.

Because of these serious challenges, several researchers and potential users have been reluctant to the possibility of such technology widespread application [4)]. The main concern is the development of tools that can be produced at a reasonable price and their lifetime. A big effort is ongoing within the technical and scientific materials science community to propose and developed materials to produce FSW tools for high melting temperature alloys [5-10)].

It is clear within this small community devoted to the development and deployment of FSW of high temperature alloys that this technology will not fully replace arc and other fusion welding processes, but it will rather take over some specific applications were the technical and specific economical advantages make it attractive. Among these fields where FSW and friction stir processing (FSP) of high temperature alloys is finding support and is being considered for some applications are automotive, nuclear, shipbuilding, and oil and gas. Even dissimilar joining of Al alloy and steel is now being used in the automotive industry production line [11)].

As part of this effort, the Materials Processing and Characterization Group at the Brazilian Nanotechnology National Laboratory (LNNano) has engaged on the study and development of FSW of dissimilar materials and high melting temperature alloys since 2006. Along this time, robust process parameters have been developed to join similar API-X46, API-X65, API-X70, API-X80[12)], duplex stainless steels (lean conventional, and superduplex) [13-16)], Ni-based alloys (Alloy 625) [17, 18)], super-martensitic stainless steels[19)], and dissimilar pairs Al/steel [20, 21)], Cu/stainless steel [22], 2507 DSS/AISI 316L [23], and A516-Gr60 steel/Alloy 625[17)]. All these joints have been submitted to detailed microstructural characterization and some of them to mechanical and chemical (corrosion) performance. In addition, an effort has been devoted to the thermal, thermo-mechanical, thermodynamic and kinetic modeling of the process and the material microstructural evolution.

Here will be presented some of the most relevant results on FSW of steel and dissimilar joints involving steel, with emphasis on the applications for the oil and gas industry.

Table 1: Some studies of FSW of steel and stainless steels.

Material	Thickness [mm]	Rotational Speed [rpm]	Travel Speed [mm/min]	Tool Material	Ref.
Cr steel	12	-	240	-	24
Low C steel	12; 15	-	102	-	24
AISI 1010	6,4	450-650	25-102	Mo, W alloys	25, 26
304L	3,2; 6,4	300, 500	102	W alloy	27, 28
304	6	550	78	PCBN	29
304L 316L	5; 10	300-700	150, 180	-	30
AL 6XN	6,4	-	102	W alloy	27
Mr. Steel	6,4; 12,7	400-450	99-120	PCBN	31, 32
HSLA-65	6,4; 12,7	400-450	99-120	W	33
API X-65	6	500	200	PCBN	34
DH-36	6,4	351-784	204-456	W alloy	35
API X-80	12; 20	250-550	100-120	PCBN WRe/PCBN	36, 37
L80	8	450/550	100	-	36
C-steel	1,6	400	25-400	WC	38
M190	1	1000	13-101	WC–8TiC–10.5NbC and TaC–8.5Co	39
HSLA-65	9,5	300-600	51-93	PCBN	40
X100	10	450	127	PCBN	41

2. FSW of API-X80 steel

12 mm thick plates of API X-80 steel were friction stir welded by two passes using AlN/PCBN and WRe/PCBN ceramic/ceramic and metal/ceramic composite tools. The tools had 25 mm shoulder diameter and 6 mm pin length. The used welding parameters and recorded conditions that produced defect-free joints were:

- Rotational speeds: 300-500 rpm;
- Travel speed: 80-120 mm/min.;
- Axial force: 26-36 kN;
- Force on the travel direction: 2,1-4,9 kN;
- Torque: 61-108 N.m;
- Energy Input: 1,69-2.10 kJ/mm;
- Max. tool temperature: 760-900 °C;
- Max. temp. measured by thermocouples at the TMAZ-AS: 877-989 °C.

The joints were produced with two passes, each one of them performed on the opposite faces of the plates. Thus, the advancing and retreating sides of the joint can be made coincident or alternated. Figure 1 shows the micro-indentation map for the alternated advancing sides joint. Notice that the SZ presents a higher hardness towards the advancing side of the joint. Therefore, two passes coincident advancing sides joints are expected to underperform mechanically and environmentally due to the aligned elevated hardness regions.

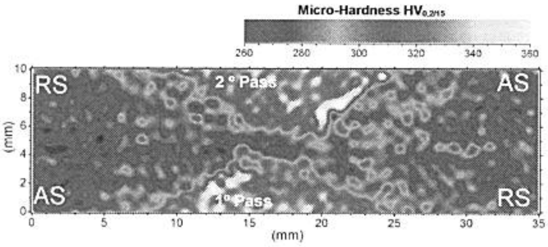

Figure 1: Micro-indentation map ($HV_{0,2}/15$) for the low energy input joint. Alternated advancing sides joint on 12mm thick API X-80 steel.

The base material, with chemical composition presented on Table 2, and the joints were submitted to exhaustive microstructural and fracture mechanics characterization. The base material (BM) presented a banded microstructure with polygonal ferrite (PF), degenerated perlite (DP), granular bainite (GB), and Martensite-Austenite (MA) constituent, as shown in Figure 2. On the other hand, the heat-affected zone (HAZ), thermo-mechanically-affected zone (TMAZ) and stir zone (SZ) presented very distinctive microstructures. The HAZ - TMAZ was formed by granular bainite (GB) and MA constituent disregarding the used parameters. The TMAZ is normally not distinguishable on steels due to the allotropic transformation, which obscures such regions. The SZ presented different microstructure depending on the energy input (heat input), where for the lower energy inputs the microstructure was predominantly formed acicular ferrite (AF) and a low fraction of bainitic ferrite (BF) and coalesced bainite (CB), as shown in Figure 3. For the higher energy inputs, the microstructure was formed predominantly by FB and low fraction of AF, CB and Martensite, this last one in very specific regions.

Table 2: API X-80 low carbon steel.

C	Mn	Si	P	S	Al	Nb	V	Ti
0,05	1,76	0,17	0,016	0,002	0,035	0,066	0,025	0,016

Cu	Ni	Cr	Mo	N	B	Ca	Ceq_{PCM}
0,02	0,02	0,15	0,20	0,0059	0,0003	0,003	0,17

Both, coincident and alternated advancing sides joints are being submitted to exhaustive fracture mechanics studies using CTOD test to determine the safe boundaries to deploy the FSW technology. Figure 4 presents some of the preliminary (more data is being collected to improve the statistics) CTOD results for the 12 mm thick coincident advancing side joints. In such figure the HAZ-AS CTOD sample notches and cracks were localized along the elevated hardness regions.

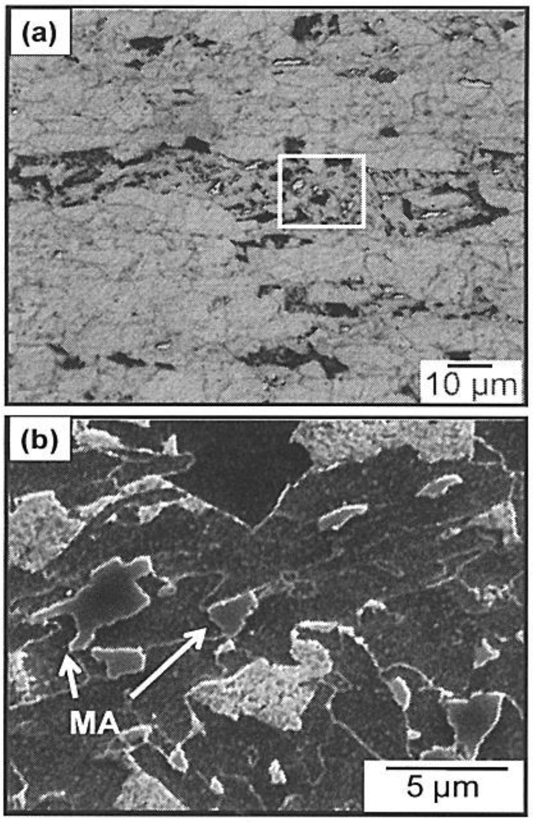

Figure 2: API X-80 base material microstructure. a. optical microscopy and b. SEM.

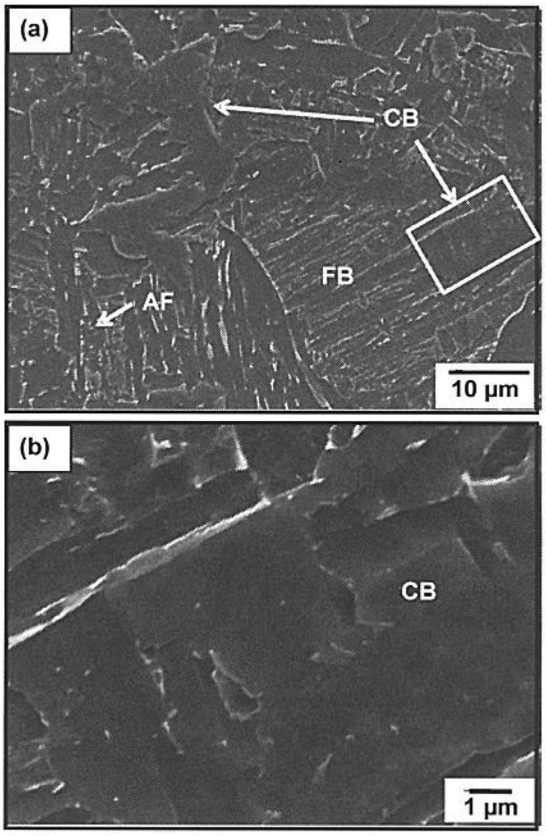

Figure 3: Low energy input SZ on API X-80 steel. a. overall view, b. CB detail.

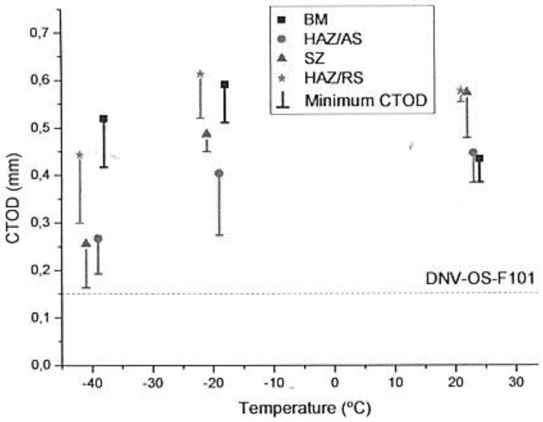

Figure 4: CTOD results for coincident advancing sides joints on 12 mm thick API X-80 steel. The symbol and lower bar represent the average and minimum value, respectively.

As can be seen in Figure 4, the 12 mm thick API-X80 FSW joints present remarkable fracture toughness down to -20 °C. Nevertheless, the SZ and HAZ-AS present slightly lower CTOD values at -40°C, when compared to the BM and HAZ-RS. Even these CTOD values are well above the average arc welding joints and the DNV OSF101 standard for offshore applications. Ongoing studies seek to develop welding conditions to further improve the joints fracture toughness and to understand the slightly lower values at the lower temperature in the SZ and HAZ-AS.

In addition, the LNNano group has also been working on the process robustness for steel pipe girth joints and underwater FSW and in both cases the results are very promising.

3. Final Remarks

As stated before, even the faced challenges for the full development and deployment of FSW of steels for the oil and gas industry, the foreseen rewards are such that several research groups around the word, some of them involving large companies, have engaged in such endeavor. Among the advantages that this technology has shown when applied to steels, should be highlighted: 1. The outstanding mechanical performance of the joints; 2. The expected process efficiency, if used to produce high quality girth joints during pipeline installation, especially on hostile environments and remote locations, conditions where the relevant tool cost is overrode by the efficiency and quality gains.

Finally, the intense research on tool materials development for high melting temperature alloys is producing important results, and nowadays some of these tools are very reliable and commercially available. In addition their cost is expected to drastically drop when they start to be produced in large quantities.

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