

Friction stir welding of structural steel S235 and S355

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1. Introduction

Since welding is a fabrication technology which involves many financial resources, the increase of welding science and technology has been phenomenal in the last decades. Welding processes are used widely in a various number of industrial fields such as construction of buildings and bridges and in the automotive, aircraft, aerospace, energy, shipbuilding and electronic industries. From 1881 when Nikolay Benardos [1] (so called “father of welding”), a Russian inventor, demonstrated the carbon electrode welding process, the welding technologies and processes known a remarkable development.

One of the youngest welding technology was patented and developed by Wayne Thomas at TWI, in 1991 and is known as Friction Stir Welding (FSW) [2][3]. The process was invented especially for the hard weldable aluminium alloys and has been widely used and investigated also for low melting materials such as Mg and Cu alloys [4]. FSW is considered to be the most significant development in metal joining in the last decades. Variations of FSW (friction spot joining friction, friction spot welding, friction riveting, injection clinching joining [5]) were also developed and are largely used in different industry fields.

It is well known that FSW reduces manufacturing costs on account of the elimination of defects, shielding gas, and costly weld preparation. Also, the process produces high-quality joints with a finer homogeneous microstructure and better mechanical properties than conventional welding processes [6]. It is a “green” technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy [2]. This process decrease most of the problems caused by the fusion welding processes because it does not involves melting and re-solidification processes of the materials to be welded. The heat causes the materials to soften, without reaching melting point (typically in the range of 70-85% of the melting temperature), and allows the pin to traverse along the joint. As the tool moves along, the material is plasticized by the frictional heat at the front of the rotating pin and transported to the back [7].

FSW involves complex interactions between a variety of simultaneous thermo-mechanical processes. The interactions affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint.

The quality of the weld seams is governed in the first instance, by the input parameters as welding speed, rotational speed and downward force and by the process parameters such as tool torque and welding tool temperature [8].

Compared to the traditional fusion welding friction stir welding exhibits a considerable improvement in strength, ductility, fatigue and fracture toughness. Moreover, 80% of yield stress of the base material has been achieved in friction stir welded aluminum alloys with failure usually occurring within the heat-affected region, whereas overmatch has been observed for friction stir welded steel with failure location in the base material. The fracture toughness of friction stir welds is observed to be higher than or equivalent to that of base material [9].

FSW offers also the possibility of joining dissimilar materials [10].

2. Friction stir welding of steels

In recent years, the research is concentrated on FSW of steels because of the major application of steels in the industries [11]. The application of FSW to the joining of steels and other high - temperature materials has not progressed as rapidly as for aluminium for important reasons. It has been limited primarily by the absence of suitable tool material that can operate at high temperatures in the 1000~1200 °C range [16]. Also, there are numerous ways in which steel can be satisfactorily and reliably welded. The consequences of phase transformations accompanying FSW have not been studied in sufficient depth.

The diversity of commercial steels available is much larger than for any other alloy system, which involves considerable experiments to optimise the weld for a required set of properties.

FSW being a solid state welding process, its application on welding of structural steel has many advantages such as elimination of welding fumes and hydrogen cracking; minimal distortion and reduction of the residual stress [12]-[13].

Previous studies [14], [15] reported that FSW achieves grain refinement in the stir zone of the carbon steel, similar to Al alloys. Furthermore, complex phase transformations also occurred in the FSW process. Hence, the mechanical properties are +partially improved compared with the base metals.

At present the most commonly used tool material for steels are polycrystalline cubic boron nitride (PCBN) and tungsten based tools. Being cost effective and too brittle, PCBN tools are being replaced with tungsten alloy tools which have been used in many early welds [14]-[18].

There has been considerable interest in exploring the use of FSW for joining steels and other higher-melting temperature materials. Few papers [21], [22] are available on friction stir welded carbon steels, but there is a need for further experimental

research to understand the fundamental mechanisms associated with the weld formation process and the welding quality.

Researches on FSW of high strength steels used for the ship building (HLSA-65) [16] were reported, also for several hard weldable stainless steel used in the medical and food industry and ultrahigh carbon steels containing 1-2 wt. % carbon [18] were investigated. Only a few investigations included more advanced characterisations of the FSW of steels, apparently none of these included analysis regarding the aspects important for structural connections, such as low cycle fatigue behaviour.

3. Research program

For the experimental procedure, two of the most used structural steel grades – S235 and S355 will be investigated. Present experiments were applied on steel grade S235JR and S355JR, to evaluate the feasibility of FSW application on structural steels. Chemical compositions are presented in Table 1 and Table 2.

Table 1. Chemical composition of S235JR.

C	Mn	P	S	N	Cu	Fe
[%]	[%]	[%]	[%]	[%]	[%]	[%]
0.17	1.40	0.035	0.035	0.012	0.55	Diff.

For these welds the parameters were selected based on previous good experience on steel A36 grade welded with FSW, with an appropriate chemical composition, mechanical and thermal properties, with the same welding machine.

Table 2. Chemical composition of S355JR.

C	Si	Mn	P	S	N	Cu	Fe
[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
0.27	0.60	1.70	0.055	0.055	0.012	0.55	Diff.

The input parameters were: welding speed – 60 mm/min, rotational speed – 750 RPM, downward force – 20 kN, tilt angle - 1°. These parameters were chosen in order to obtain welds with good surface aspect and defect free. The process took place in terms of position control.

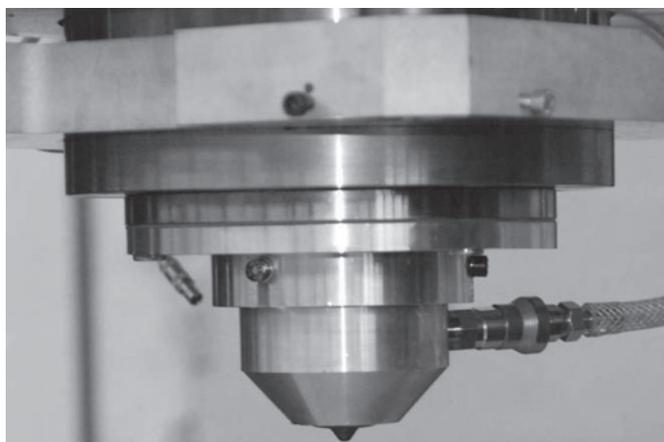


Figure 1. PCBN welding tool.

The welds were produced with a guttering machine, property of Helmholtz-Zentrum Geesthacht Centre for Materials and

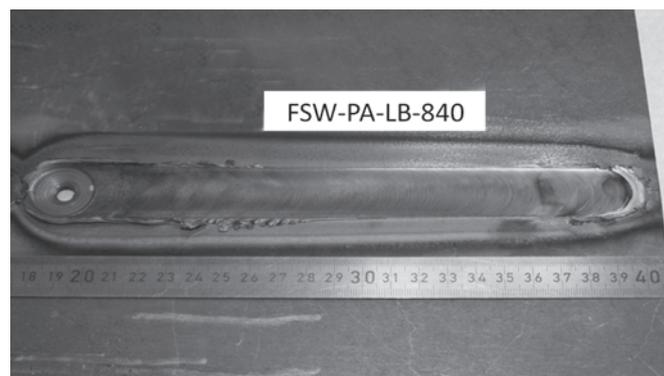
Coastal Research, Germany. For all the welds a PCBN tool was utilised, with a shoulder diameter of 36.8 mm and a pin diameter of 9.2 mm. The pin length was setup at 3.8 mm (see Figure 1).

The dimensions of the plates were: 4 mm thickness, 100 mm wide and 500 mm long. The surfaces of all to be weld plates were prepared by a mechanical cleaning with grinding paper and chemical with ethanol, in order to remove the oxides layers that may interfere in the quality of the weld seam. In previous welding trials, it was observed that the oxide layers from the surface of the plates/elements, affect the quality of the connections.

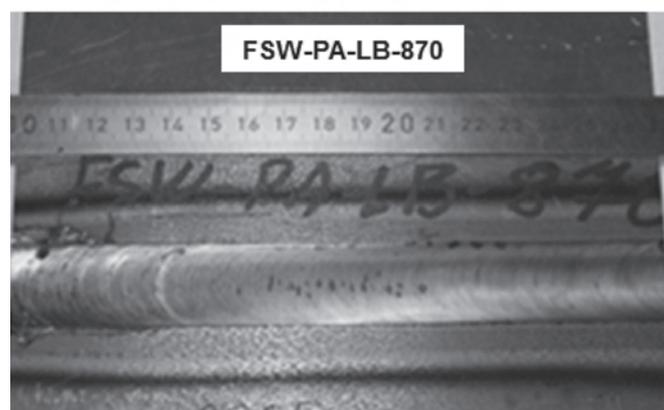
In order to minimize the temperature introduced in the welding tool, the weld seams realized in one step were approximately 200 mm long (see Figure 2).

From each welded plate, the first 20 mm of the plate were not used in test specimens' preparation, in order to exclude the possible instabilities zones caused by the reduced temperature of the welding tool. These parts were still used for the investigation of the presence of root defects such as lack of penetration.

Specimens for macro-structure analysis, hardness measurements and bending tests were extracted from all welded plates, starting from the key hole, towards welding direction.



a)



b)

Figure 2. Surface aspect of the steel friction stir weld: a. – S235JR; b. – S355JR.

The cross-section was perpendicular to the welding direction and then mechanical and chemical polished. The samples were prepared according to standard metallographic practice and etched in a nital (alcohol and nitric acid solution) solution with a 95% concentration, for 50 seconds. Optical microscopy (OM) observations of each FSW joint were carried out.

The Vickers hardness profile of the connections was measured on the cross-section perpendicular to the welding direction, with a 0.98N load for 15 s, using a Zwick-Roell Indentec hardness measurement machine. The measurements were realized on three lines, along the cross-section, established to a 1 mm distance from the edges and between them.

The bending test were realized on a machine for bending in three points.

4. Preliminary results

The first visual inspection relieved the increase of the downward force. This phenomenon is emphasised by the material pullout in the last part of the weld. In order to evaluate also the existence of root defects, bending tests were realized. For each analyzed connection, no root defects were found. This could also be observed in the macrostructure analysis.

A macroscopic overview of the cross-section of the weld is shown in Figure 3. A dark grey region is observed around the weld centre. It is noted that this region is wider than the diameter of the tool shoulder at the top surface.

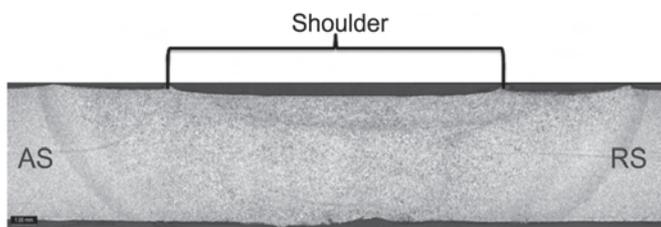


Figure 3. Typical macrostructures for a single-pass full penetration friction stir weld in S235JR steel made using a PCBN tool.

The macrostructure of the weld can be split into several distinct regions. These are the weld nugget (N) or stirred zone (SZ); a region either side of the weld nugget termed as thermo-mechanically affected zone (TMAZ); the heat affected zone (HAZ) and the base material (BM) (see Figure 4). In comparison with the cross section of others materials, to steels the TMAZ area is significantly larger. This is caused by the large amount of the temperature introduced in the plates during the welding process.

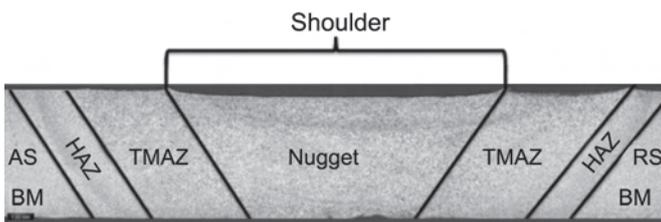
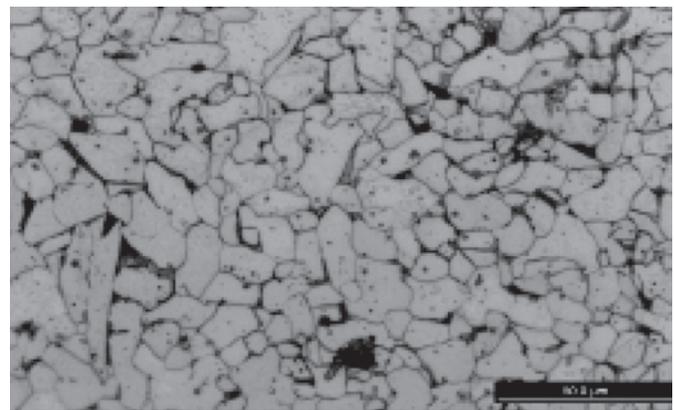


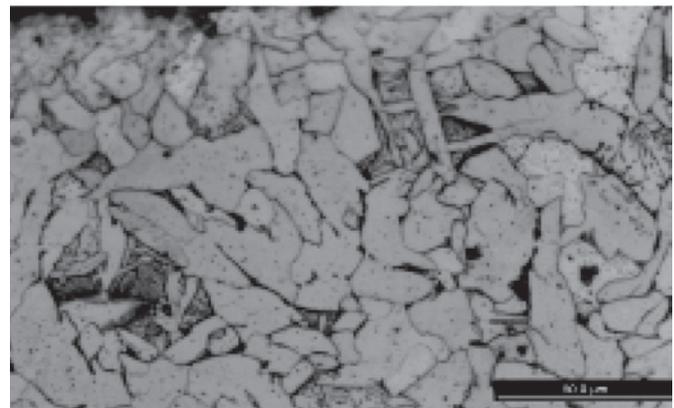
Figure 4. Specific regions of the FSW cross-section.

The microstructure evaluation of each region of the connection cross section was carried out. Significant grain changes were observed along the new formed zone in the cross section of the connection.

Thus, the base material grains in the HAZ tend to grow due to the significant amount of heat generated during FSW. The original grains distribution is homogeneous, and the microstructure of this region is similar to that of the BM except for the grain size (see Figure 5).

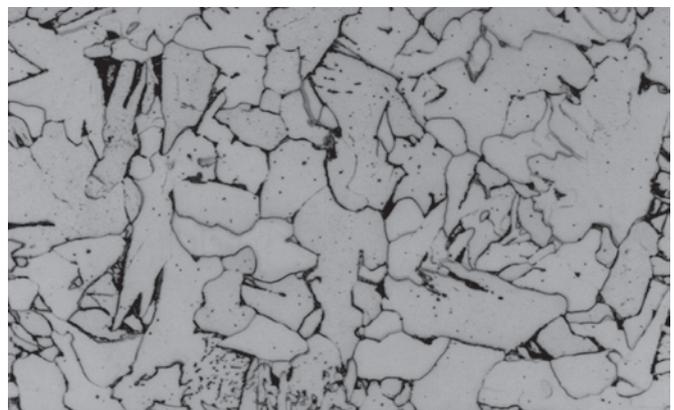


a)



b)

Figure 5. Microstructure of the FS welded S235JR base material (a) and HAZ (b).



a)

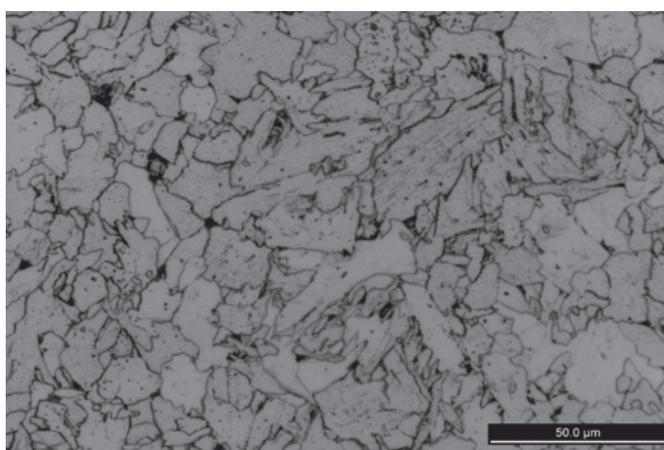


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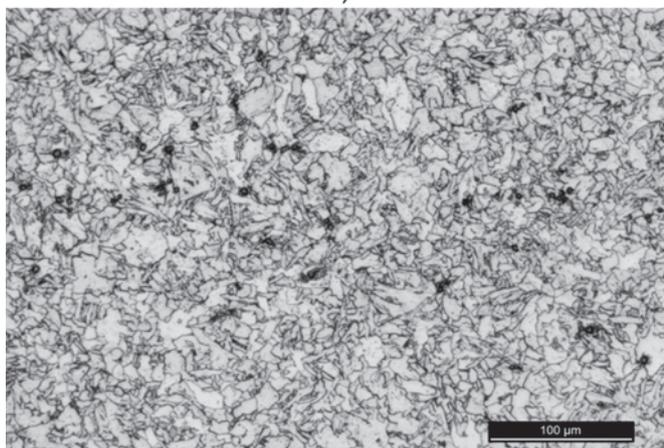
Figure 6. Microstructure of the FS welded S235JR TMAZ (a) and SZ (b).

The grain distribution in the TMAZ is considerably a fine homogeneous one, in comparison to that observed in the stirred zone (see Figure 6). The fine-grained microstructure in the TMAZ was attributed to the continuous dynamic re-crystallization induced by the substantial shear deformation and significant amount of heat generated during FSW. The continuous dynamic re-crystallization [19], which is an interesting microstructural characteristic of the TMAZ, would be associated with the progressive transformation of sub-grains into new grains within the deformed grains as well described in the literature [20].

The structure morphology observed in this the stirred zone (SZ) is quite distinguishing and can be annotated considering the phase transformation that occurs during FSW. The austenite-to-ferrite transformation occurs in the SZ during FSW, and this phenomenon would result in a specific SZ completely different from the other friction stir welded regions [23][24]. The same evolution in the weld zone was observed also for the macros of S355JR FSW welds.



a)



b)

Figure 7. Microstructure of the FS welded S355JR TMAZ (a) and SZ (b).

Hardness profiles of the welds are presented in Figure 8. Basically the hardness within the weld regions is higher than the base metals.

The increasing of the hardness values in the stirred zone may be induced by the formation of bainitic ferrite, caused by the dynamic re-crystallization that attends the FSW process. Higher values for the hardness were obtained from a hardness mapping, also indicating an increase of the values, in comparison with the values for the base material. The peaks from the hardness measurements can be explained by the presence of the martensite (Figure 8).

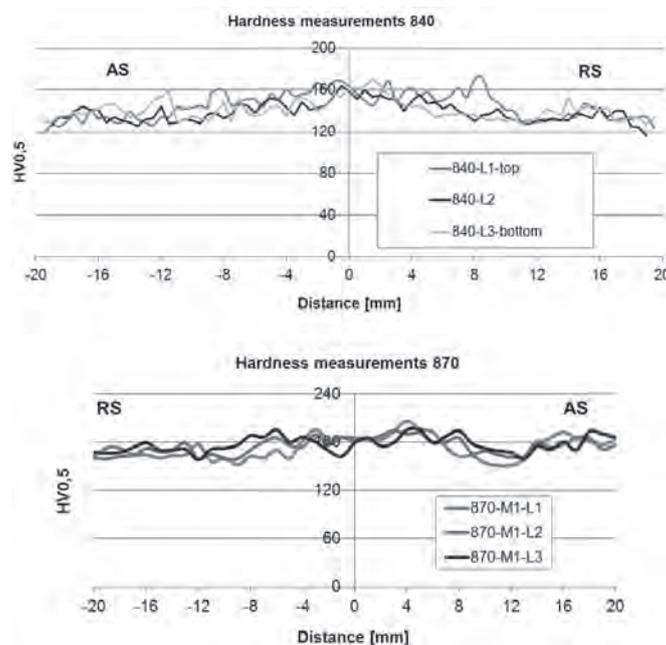


Figure 8. Hardness measurements.

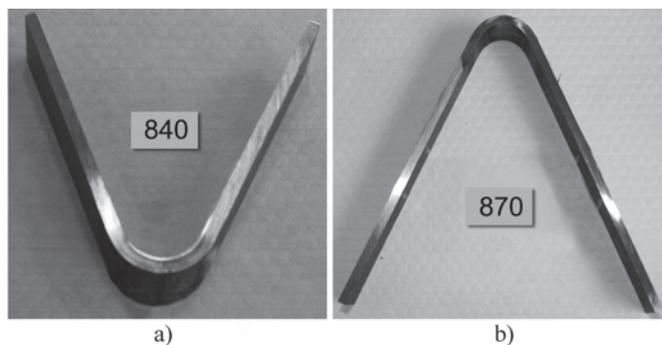


Figure 9. Bending tests on a) S235JR and b) S355JR.

The bending tests presented a good ductility of the weld root; no defects were present in this region of the welds for both materials.

5. Conclusions

FSW is a promising relatively new welding technology, with a very high potential especially due to reduces residual stresses, homogeneous microstructure in the heat affected zone and with excellent toughness and ductility of the weld zone. However, apparently there are no studies on the cyclic behaviour in the low cycle fatigue range of steel components connected using FSW.

While additional advances are required in processes and pin tools to ensure economic viability in industrial applications, FSW could prove to fulfil one of the predicted needs for innovation in steel design and construction. In order to implement the application of FSW process to structural steel components, a more detailed characterization and understanding of the weld seams must be carried out, including the behaviour under the LCF impact. Therefore there is a high interest in assessing the potential of FSW as an alternative to conventional fusion welding, as well as implementation of FSW specific guidelines in design codes.

The actual experimental program indicates that structural steel plates S235JR and S355JR with a thickness of 4 mm can be successfully friction stir welded.

Microstructure is known to affect fatigue strength, the crack initiation and propagation of crack present in the weld metal. Grain size and morphology plays a vital role to the improvement of fatigue performance. Theoretical, the effect of FSW process on structural steel S235JR and S355JR microstructure leads to an improved fatigue life.

The repeatability of the process, using the same welding parameters and conditions, is not clearly. Different characteristic were observed on the connections realized on the same plates.

Taking into account the improvements of the macro- and microstructure in comparison with the one obtained during the fusion weld processes, FSW of structural steels can be considered a solution especially for the structural connections subjected to low cycle fatigue. However, more detailed analysis are needed to inspect all the aspects regarding the industrial application of the process and the important characteristics required for connections subjected to major loads, such as seismic loads in case of civil engineering.

There are other difficulties, and claims of success may be premature given that the level of characterisation of mechanical properties is far less than that required in structural applications. The focus also must be on cost if real success is to be achieved, although this would be mitigated by the identification of critical problems which are not well addressed by established methods of joining steels.

From a very recently report of Brian Thompson about the successful weld of a 25 mm thick steel plate new directions were opened for FSW of steels [25].

Future work will present the evaluation of tensile behaviour of the welds in comparison with base material, also the influence of temperatures introduced during the welding process on the distribution of residual stresses in the weld and the vicinity of the weld.

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