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Microstructure, mechanical properties and microtexture of friction stir welded S690QL high yield steel

Pascal Paillard [a], Emmanuel Bertrand [a,*], Marion Allart [b], Alexandre Benoit [b], Guillaume Ruckert [c]

[a] Institut des Matériaux Jean Rouxel, UMR 6205, Polytech Nantes, Site de la Chantrerie, BP 50609, 44306 Nantes cedex 3, France
[b] Institut de Recherche Technologique Jules Verne, Chemin du Chaffault, 44340 Bouguenais, France
[c] DCNS Research, Technocampus Ocean, 5 rue de l'Halbrane, 44340 Bouguenais, France

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ABSTRACT

Two try-out campaigns of friction stir welding (FSW) were performed with different friction parameters to join S690QL high yield strength steel. The welds were investigated at macroscopic and microscopic scales using optical and electronic microscopy and microhardness mapping. Welds of the second campaign exhibit microstructures and mechanical properties in accordance with requirements for service use. Microtexture measurements were carried out in different zones of welds by electron backscattered diffraction (EBSD). It is shown that that texture of the bottom of the weld is similar to that of the base metal, suggesting a diffusion bonding mechanism. Finally, the mechanical properties (tensile strength, resilience, bending) were established on the most promising welds. It is shown that it is possible to weld this high yield strength steel using FSW process with satisfactory geometric, microstructural and mechanical properties.

1. Introduction

Friction stir welding (FSW) was developed by TWI (The Welding Institute) in the early 1990s [1]. It enables the joining in solid state of metals which are difficult to join by fusion welding due to their metallurgical structure as aluminum alloys of the 2000, 6000 and 7000 series. For this type of alloys, many studies on the feasibility of assemblies and numerical modeling of the process were conducted. Due to the low melting point of aluminum and its alloys, the temperatures which are necessary to soften the metal during FSW process are relatively low. The real challenge is to extend this process to metallic alloys with higher melting point (above 1000 °C) such as steels, titanium, or nickel alloys [2].

FSW principle remains the same for any intended material. This is a solid phase welding process which requires the mixing of the material in a pasty state at the weld bead using a rotary tool. The rotary tool is generally composed of a conical spin and a shoulder for heat generation by friction (Fig. 1a). However, the design of the tool may be more complex to weld high melting point alloys. When steels are joined by FSW, parameters for tool input such as vertical force, rotation speed and tool shape are critical. Indeed, the metal at room temperature exhibits high mechanical properties and must be heated only by friction of the tool to reach the pasty state but this operation can affect its useful mechanical properties. Hence, significant vertical forces (up to several tens of kN) are raised during this phase [3,4]. Generally, this process induces several affected zones in the base metal (BM): the stir zone (SZ) which is mixed, the thermomechanically affected zone (TMAZ) and the heat affected zone (HAZ) (Fig. 1b).

However, the major advantage of FSW in the context of future industrialization is the high mechanical properties and high performance in service of the resulting welded joints. Few works can be found on FSW of high yield strength steels. Most of these studies, conducted on various steels, characterized the tensile strength, the fracture energy and the toughness of the weld bead. Among them, Chung et al. [6] and Fujii et al. [7] obtained fractures in the base metal during tensile tests on FSW welds performed on steels containing different amounts of carbon (IF, S12C and S35C), showing that mechanical resistance is higher in the weld bead. However, they also observed a decrease of the resilience in the same zone, which can be significant depending on the welding conditions.

Drop of resilience in steels is generally caused by the modification of microstructural features such as formation of martensite [8]. The brittleness of these components strongly depends on the chemical composition and the microstructure of the base metal, and also on the thermomechanical treatment received due to the welding process. However, some trends can be outlined.

However some trends can be outlined. Miles et al. [9] investigated the influence of the welding speed and the rotational speed of the tool on the shape and microstructure of the zones during a FSW run using a MegaStir tool in bulk boron nitride. The tests were made using a wide range of parameters on steels for automotive applications (DP590, DP980 and TRIP590) that have yield strengths between 600 and 1000 MPa and a ferritic-martensitic initial microstructure. They

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* Corresponding author.
E-mail address: emmanuel.bertrand@univ-nantes.fr (E. Bertrand).

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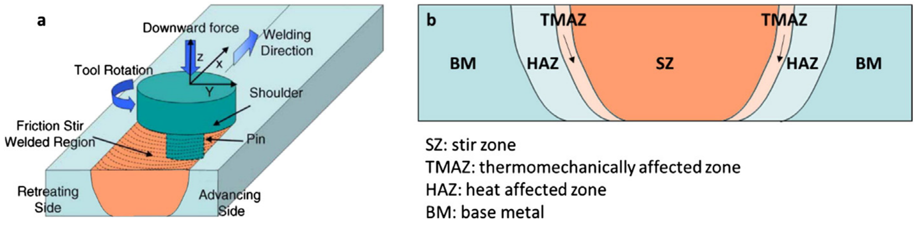

Fig. 1. Schematic drawing of friction stir welding (inspired from [5]) (a) and schematic of a cross-section macrograph showing the different zones of the weld (b).

noted that for so-called "cold" welding conditions (low speed, high feed rates) the material probably never reached the austenitization temperature. For "hot" welding condition (high rotational speeds, low feed rates), the temperature in the friction stirred region reached the austenitic domain. Nevertheless, they found optimal parameters for each steel, although it appeared complicated to determine the nature of the phases (including bainite presence). These parameters are often a compromise between the "hot" conditions — which limit tool wear but may induce brittle microstructures in weld — and the "cold" conditions — which are more damaging for the tool but help avoid brittle microstructures. Additional work have confirmed this finding [10,11], which can be explained by the higher tool rotational speed which generates more heat to the material. Similarly, as the welding speed is increased, most of the heat locally generated is used to maintain the material temperature. Hence the cooling rate decreases and the material gets hotter.

Finally, Barnes et al. [12] took interest in the metallurgical transformations that take place during the friction stir welding of the RQT-701 (closely related to the S690QL steel for naval application in terms of chemical composition and mechanical properties). In particular, they observed a transition zone is the HAZ in terms of metallurgical constituents. While parts of the HAZ closer to the nugget had a martensitic structure similar to that of the kneaded area, HAZ closer to the base metal has displayed fine grains of ferrite and pearlite. This study also showed that it can be difficult to clearly differentiate the TMAZ from the HAZ.

To the knowledge of the authors, no work has ever been published regarding FSW of the S690QL steel. This work aims to show that it is possible to join 8 mm plates of S690QL high yield strength steel using FSW process without developing brittle microstructures and with satisfactory mechanical properties.

2. Material and Methods

S690QL steel (EN steel number 1.8928) is a high yield strength steel which is used in construction and in shipbuilding to lighten structures. It has a guaranteed minimum yield strength of 690 MPa and is supplied in the hardened and tempered state. Its chemical composition is given in Table 1. The welding sheets used here have a thickness of 8 mm, a width of 400 mm and are 1000 mm in length. Welds are made along the length of the sheets. Two welding test campaigns were conducted at MEGASTIR society. Welding parameters and tool geometry details cannot be mentioned in this article for confidentiality reasons. The second campaign allowed the optimization of the process based on results of the first one. A tool with a larger pin diameter and a larger shoulder diameter is used for the second campaign. Moreover, the rotation speed of the tool was reduced by 35%, the welding speed was kept constant and the vertical load was increased by 120% in order to optimise the quality of the weld. The pseudo heat index can be defined as ω^2/v where ω is the rotation speed of the tool and v the welding speed [5]. Parameter optimization makes heat index drop from 400 mm^{-1} to 180 mm^{-1}. Moreover, the temperature of the rotary tool was measured using a thermocouple directly inserted inside it and these measurements showed the maximum temperature reached in service is lower than 700 °C.

50 mm ∗ 8 mm cross-sections samples are taken from the welds, from a significant distance from the beginning and the end of the weld. They are prepared by mechanical polishing until a "mirror polished" state is reached. Macrostructures (i.e. structures at a mesoscale) are then revealed by chemical etching using Nital 5 (5%vol HNO_3 in ethanol) and observed using a ZEISS optical microscope. Vickers microhardness maps are done on "mirror polished" samples with a load of 1 kgf on a Durascan (Struers) automatic hardness tester. Micrographic and EBSD studies are carried out using a Merlin scanning electron microscope (SEM) from Carl Zeiss equipped with a Nordlys 2 camera. Inverse pole figures are calculated using HKL Tango software, where pole densities are given in multiple of uniform density (MUD) unit. The maximum of the MUD scale represents the strength of the texture, compared to a random distribution (whose maximum is equal to 1).

The methodology of mechanical testing, including bending tests, tensile tests and Charpy impact tests, will be detailed in the dedicated section.

3. Results and Discussion

3.1. Preliminary Tests and Macroscopic Study

Preliminary microhardness measurements are carried out in order to confirm the hardenability of S690QL, and for comparing values before and after FSW. Ten microhardness tests are performed on (i) the base metal (BM), and on the base metal after austenitization at 850 °C for 15 min and (ii) water quench (WQ), (iii) oil quench (OQ) or (iv) air quench (AQ). Average values are given in Table 2 and confirm hardenability of S690QL. The hardened and tempered state of the base metal is slightly higher than that of AQ state. These values are inserted in Fig. 2e as a comparison with the local mechanical properties after FSW.

Fig. 2 shows cross section macrographs of welds of the first campaign (W1) and of the second campaign (W2) together with the corresponding microhardness maps. From the geometrical aspect, cross sections show no dissymmetry between advancing and retreating side. Table 3 shows width of SZ of W1 and W2. As the tool is larger for W2, SZ is also larger: 14.6 mm versus 10.0 mm for W1. Welds are homothetic in width: ratio between the three measures are quite similar from W1 to W2. SZ are also rather flared with a top/bottom ratio higher than 3.

Table 1
chemical composition (% mass) of the S690QL steel.

C	Si	Mn	P	S	N	B	Cr
0.18	0.50	1.60	0.020	0.010	0.015	0.005	0.80
Cu	Mo	Nb	Ti	V	Ni	Zr	
0.50	0.70	0.062	0.050	0.10	2.00	0.15	

Table 2
Microhardness of S690QL steel (BM) before and after austenitization at 850 °C and quench in water (WQ), oil (OQ) and air (AQ).

State	BM	WQ	OQ	AQ
Microhardness (HV1)	255	418	386	250