Materials Characterization 110 (2015) 126–135

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Microstructural characterisation of friction stir welding joints of mild steel to Ni-based alloy 625

J. Rodriguez [a,b], A.J. Ramirez [a,b,c,*]

[a] Brazilian Nanotechnology National Laboratory (LNNano), P.O. Box 6192, Campinas, SP, Brazil
[b] University of Campinas (UNICAMP), Campinas, SP, Brazil
[c] Department of Materials Science and Engineering, The Ohio State University — OSU, Columbus, OH 43221, USA

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 16 October 2015
Accepted 19 October 2015
Available online 19 October 2015

Keywords:
Characterisation
FSW
Mild steel
Alloy 625

ABSTRACT

In this study, 6-mm-thick mild steel and Ni-based alloy 625 plates were friction stir welded using a tool rotational speed of 300 rpm and a travel speed of 100 $mm \cdot min^{-1}$. A microstructural characterisation of the dissimilar butt joint was performed using optical microscopy, scanning and transmission electron microscopy, and energy dispersive X-ray spectroscopy (XEDS). Six different weld zones were found. In the steel, the heat-affected zone (HAZ) was divided into three zones and was composed of ferrite, pearlite colonies with different morphologies, degenerated regions of pearlite and allotriomorphic and Widmanstätten ferrite. The stir zone (SZ) of the steel showed a coarse microstructure consisting of allotriomorphic and Widmanstätten ferrite, degenerate pearlite and MA constituents. In the Ni-based alloy 625, the thermo-mechanically affected zone (TMAZ) showed deformed grains and redistribution of precipitates. In the SZ, the high deformation and temperature produced a recrystallised microstructure, as well as fracture and redistribution of MC precipitates. The $M_{23}C_6$ precipitates, present in the base material, were also redistributed in the stir zone of the Ni-based alloy. TMAZ in the steel and HAZ in the Ni-based alloy could not be identified. The main restorative mechanisms were discontinuous dynamic recrystallisation in the steel, and discontinuous and continuous dynamic recrystallisation in the Ni-based alloy. The interface region between the steel and the Ni-based alloy showed a fcc microstructure with NbC carbides and an average length of 2.0 μm.

1. Introduction

Dissimilar welds between Ni-based alloys and ferritic steels have been used in engineering in a wide range of applications, including pressure vessels and oil exploration [1]. In general, the applications take advantage of the excellent corrosion and oxidation properties of Ni-based alloys in combination with the low cost of steels. Ni based alloy 625 is used in the construction of a large number of power plant components that require creep, thermal-fatigue and corrosion resistance. In contrast, the steel ASTM A516 is used mainly for the construction of equipment components for the oil industry, and it has the highest tensile strength and ductility of conventional pressure vessel steels. In corrosive environments, this steel has the longest time to fracture [2]. Fusion welding is usually employed to join steel to Ni-based alloys, most often used in cladding. However, there are process and metallurgical challenges associated to this dissimilar joint. On the process side, there are large differences in melting temperatures and fluidity that may lead to lack of fusion defects. Regarding the metallurgical weldability, there are solidification cracking, hard interfacial regions, materials intermixing and C diffusion issues that may compromise the joint performance [1,3]. In addition, the mechanical and corrosion properties may be compromised due to the as cast structure [4,5]. Therefore, performing solid state joining of these alloys overcomes or minimises some of the aforementioned challenges, making it a promising alternative [1].

Friction stir welding (FSW) is a solid state joining technique developed at TWI in 1991 [6–9]. A non-consumable tool rotates and travels along the joint or material being processed [10]. Heat generated by friction and deformation softens the material, which flows under severe plastic deformation condition [7]. FSW has become a viable and important manufacturing alternative in several industries. Although, it was originally developed for joining light Al and Mg alloys, this technique has evolved to become useful with higher-melting-temperature alloys, such as steel, titanium and Ni-based alloys [11].

The use of FSW for joining Ni-based alloys, particularly alloy 625, has resulted in significant grain size refinement in the stir zone compared to the base material [4]. In addition, there have been enhancements to the material's mechanical properties due to the refined grain size. Similar improvements to mechanical properties have been reported for alloys 600 and 718 welded using FSW [12–14]. In the case of dissimilar FSW joints involving steel and Ni-based alloys, there are few reports in the literature [15,16]. Song et al. [15] studied the microstructure and

* Corresponding author at: Department of Materials Science and Engineering, The Ohio State University — OSU, Columbus, OH 43221, USA
E-mail address: ramirezlondono.1@osu.edu (A.J. Ramirez).

http://dx.doi.org/10.1016/j.matchar.2015.10.023
1044-5803/

Table 1
Chemical composition (wt.%) of ASTM A516 Gr 60 carbon steel and Ni-based alloy 625.

Element	Ni	Cr	Mo	Nb	Fe	Si	Ti	Al	Mn	Co	C
A516*	0.01	0.03	–	–	Bal	0.25	–	0.29	0.95	–	0.15
A625*	60.72	22.59	9.39	3.50	3.,00	0.22	0.24	0.18	0.09	0.05	0.02

* Chemical composition provided by the manufacturer.

mechanical properties of a lap joint of alloy 600 to low carbon steel. The results showed friction stir lap joints without defects, notable grain refinement in the stir zone and improvement of mechanical properties. In addition, the formation of a steel hook in the alloy 600 was observed. This hook, formed at the interface, enhanced the joint peel strength. In previous publications [16], grain size refinement in the heat-affected zone and allotriomorphic and Widmanstätten ferrite formation in the stir zone of the low carbon steel were found. For alloy 625 the dynamic recrystallisation led to austenite grain refinement. However, the microstructural character of FSW dissimilar butt joints of steel to a Ni-based alloy has not been reported. In the current study, the microstructure character of butt joints steel to Ni-based alloy is described.

2. Experimental procedure

ASTM A516 Gr 60 (A516) carbon steel and Ni-based alloy 625 (A625) plates (500 × 90 × 6.6 mm) were friction stir welded using a W-Re PCBN (polycrystalline cubic born nitride — PCBN) composite tool in force control mode. The alloy compositions are presented in Table 1. The tool's rotational speed and travel speed were 300 rpm and 100 mm·min^{-1}, respectively. The development and selection of

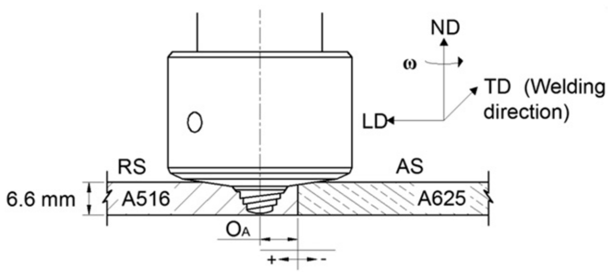

Fig. 1. Schematic of the joint configuration for FSW of A516 steel to Ni-based alloy 625. The tool axial offset (OA) is shown. Plus and minus represent the position of the tool relative to the joint line. ND: normal direction, TD: transverse direction and LD: longitudinal direction.

welding parameters are shown elsewhere [17]. An axial offset of 1.63 mm (Fig. 1) and an axial force of 30 kN were used. The axial offset (O_A) represents the distance from the tool axis to the joint line.

Vickers microhardness tests were performed on the cross-section perpendicular to the welding direction using a 0.98 N load and 15 s dwell time. The microstructure of the welded zones was observed by optical microscopy (OM) and scanning electron microscopy (SEM). In addition, a chemical analysis was carried out using energy dispersive X-ray spectroscopy (XEDS). The samples were prepared using a standard metallographic procedure followed by etching. For the OM and SEM samples, the steel was etched with Nital 2%-vol and the alloy 625 was etched with an aqueous solution of H_2CrO_4 10%-vol at 2.5 V for 20 s. Three regions (the stir zone of each material and the interface between the steel and the alloy 625) were selected for detailed examination by transmission electron microscopy (TEM). For the TEM samples, thin-foil disc specimens 3 mm in diameter were cut from the stir zone of the alloy 625 and mechanically polished to a thickness of 200 μm. The disc specimens were dimple ground to a thickness of 20 μm, and the central area each specimens was polished using ion milling. The specimens from the stir zone of the steel and the interface were prepared using a focused ion beam (FIB) following the standard procedure.

3. Results and discussion

The FSW parameters used produced sound welds without cracks or cavities. The solid-state nature of and lack of melting in FSW eliminated the problems of solidification and cracking. Fig. 2 shows a low magnification optical image of the weld cross-section. The material flow caused by the tool rotation and displacement during FSW caused the formation of a vortex-like shape in the weld, which has been also seen in dissimilar FSW of other alloys [18]. The plastic deformation caused some portions of material from the advancing side (AS) to be dragged to the retreating side (RS) and vice versa, resulting in alternating bands of the two materials in the stir zone. In the low-magnification optical micrograph of the weld cross-section, several microstructurally distinct regions can be seen. The regions in the steel were the base material (BM_{A516}), the inter-critical heat-affected zone ($ICHAZ_{A516}$), the fine-grained heat-affected zone ($FGHAZ_{A516}$), the coarse-grained heat-affected zone ($CGHAZ_{A516}$), and the stir zone (SZ_{A516}). Unlike the welds on Al alloys and fcc materials, no thermo-mechanically affected zone (TMAZ) was observed in this weld [19,20]. The allotropic transformation undergone by the steel during cooling naturally obscures the microstructural evidence of deformation associated to the process, which makes the TMAZ unequivocal identification challenging. In the Ni-based alloy, the identified regions were the base material (BM_{A625}), the thermo-

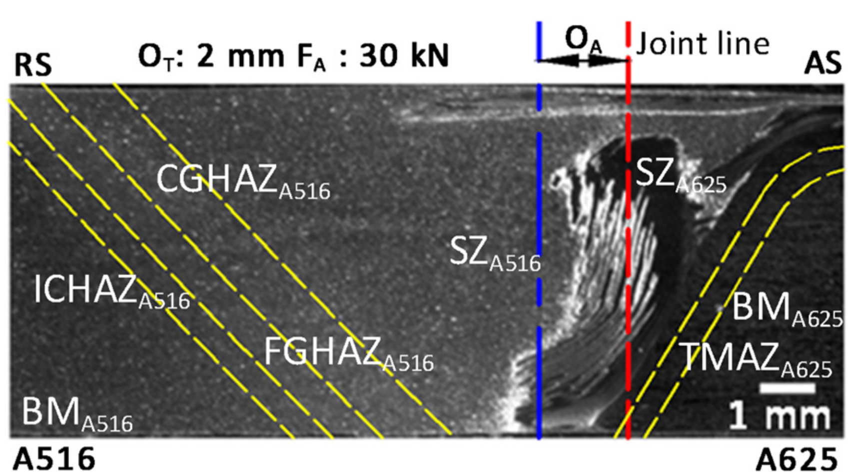

Fig. 2. Different microstructural regions in the cross-section of the weld. In the steel, BM_{A516}, $ICHAZ_{A516}$, $FGHAZ_{A516}$, $CGHAZ_{A516}$, and SZ_{A516}, and in the Ni-based alloy BM_{A625}, $TMAZ_{A625}$, and SZ_{A625}. Dashed lines schematically represent the size of each region based on the microstructural characterisation.