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Microstructure and mechanical properties of a thick-section high-strength steel welded joint by novel double-sided hybrid fibre laser-arc welding

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ABSTRACT

In this paper, a novel double-sided hybrid fibre laser-arc welding procedure was developed to join 30 mm thick, high-strength steel, and this procedure was compared with conventional double-sided arc welding. The welded joint was divided into two zones, the laser zone and the arc zone, and the microstructure and mechanical properties of the welded joint in these zones were investigated in detail. The results indicated that the laser zone and arc zone predominately consisted of lath martensite with a high dislocation density. The average grain sizes of the laser zone and the arc zone were smaller than that of the base metal. The results also indicated that the laser zone and the arc zone possessed higher strength when compared with the base metal because of the fine lath martensite. Meanwhile, the strength observed in the laser zone was slightly higher than that of the arc zone due to the small average effective grain size. On the contrary, the toughness of the base metal was higher than the toughness in the laser zone and the arc zone because of massive polygonal ferrites. Meanwhile, a significant increase in the toughness of the laser zone when compared with the arc zone occurred due to an increase in the prevalence of grain boundaries with large misorientation angles.

1. Introduction

With a good combination of strength and toughness, thick-section high-strength steels are currently widely used in pipeline construction [1,2] and in the shipbuilding industry [3,4]. The common welding techniques used for thick-section high-strength steels are multi-pass shielded metal arc welding (SMAW) [5,6], gas tungsten arc welding (GTAW) [7,8], gas metal arc welding (GMAW) [9], flux cored arc welding (FCAW) [10], and submerged arc welding (SAW) [11–13]. Although these methods can satisfy the requirements for quality, the welding efficiency is very low because of their low penetration depth. Therefore, there is an exigent need to develop advanced welding techniques with deep welding penetration for joining thick-section high-strength steels.

Recently, hybrid laser-arc welding (HLAW), which allows for increased gap tolerances while retaining the penetration necessary for the efficient welding of thicker workpieces when compared to laser welding, has been developed [14–17]. Excellent quality welds without incomplete fusion, porosity, hot cracks or humping of high-strength steel have already been successfully produced using HLAW [18–20]. Additionally, Moore et al. [21] reported that the HLAW process prevented the problems associated with the rapid cooling and solidification crack susceptibility of laser welding, resulting in significant improvements of the microstructures and mechanical properties of welded joints. Roepke and Liu [22] also stated that excellent mechanical properties of an HY-80 steel welded joint were achieved by HLAW. Furthermore, full penetration in thick-section high-strength steel was successfully obtained using HLAW with a high-power fibre laser, which greatly improved the welding efficiency. Cao et al. [23] developed an HLAW process using a 5.2 kW fibre laser and obtained full penetration in 9.3 mm thick high-strength steel. Their research indicated that, when compared with the conventional arc welding with three passes, the HLAW joined the thick plates with only one pass. Grünenwald et al. [24] focused on the high-power fibre laser-arc hybrid welding of high-strength pipe steel and confirmed that, with a maximum laser power of 8 kW, two weld passes and proper joint preparation were needed to join 14 mm thick X70 steel. Their results demonstrated the advantages of HLAW, including the saving of filler material, as well as a reduced number of welding passes; they also demonstrated that these advantages contribute to higher productivity and lower production costs. Inspired by double-sided arc welding (DSAW) [25–27], a novel double-sided hybrid laser-arc welding (DSHW) system was designed to utilise the advantages of HLAW outlined in this paper. In this study, thick-section high-strength steel was joined by DSAW

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and DSHW. The microstructure of the weld metal by DSHW was studied in detail. The mechanical properties, including the tensile strength and the impact toughness, were also analysed.

2. Experimental procedure

High-strength steel with dimensions of 700 mm × 165 mm × 30 mm and filler wire with a diameter of 1.2 mm were used in this study. Their chemical compositions are listed in Table 1. In addition, a mixture of 05% Ar and 5% CO_2 with a flow rate of 25 l/min was used as a shielding gas. To obtain full penetration of the weld in the thick-section steel, a butt joint with a K-groove configuration was prepared, as shown in Fig. 1a. The four-pass welding sequence is shown in Fig. 1b. The specimen surfaces were cleaned with acetone before welding to eliminate surface contamination.

Table 1
Chemical composition of high strength steel and filler wire (wt.%).

	C	Si	Mn	P	S	Ni	Cr	Mo
Steel	0.11	0.25	0.57	0.010	0.008	4.47	0.60	0.40
Wire	0.05	0.40	1.72	0.009	0.009	2.50	0.60	0.60

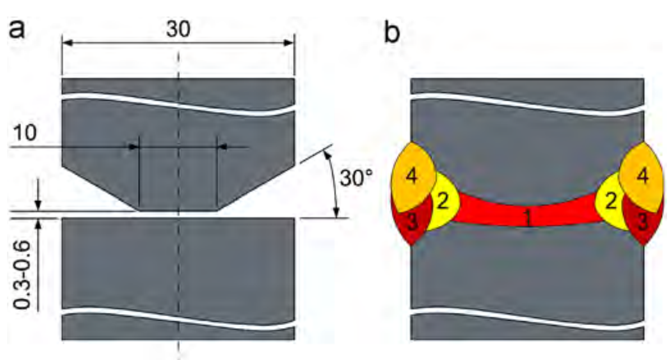

Fig. 1. Schematic of: (a) the groove shape and (b) the welding sequence of DSHW with four passes.

Table 2
Characteristics of fiber laser system.

Wavelength (μm)	Process fiber core diameter (μm)	Collimation length (mm)	Focal length (mm)	Beam parameter product (mm · mrad)
1.07	200	150	200	7.3

The welding system consisted mainly of two IPG Photonics Corporation (Ytterbium laser system (YLS)-5000 and YLS-10000) continuous wave (CW) solid-state Ytterbium fibre laser systems and two Fronius (Transpuls synergic (TPS)-4000) welding power supplies with a maximum arc current of 400 A. The maximum powers of the two laser systems are 5 kW and 10 kW, and the main characteristics of the laser systems are shown in Table 2. In addition, two Keller und Knappich Augsburg (KUKA) (KUKA robot (KR) 16-2) welding robots were used. As shown in Fig. 2a, DSHW consists of two HLAW, which are symmetrically laid on both sides of the workpiece in a horizontal position. The laser welding head and the arc torch were fixed to a welding robot, and the welding was completed with the laser leading the arc in the welding sequence with four passes. The welding velocity (v), the distance (D) between the laser and the arc, the angle (α) between the laser and the horizontal surface, the angle (β) between the arc torch and the horizontal surface, and the angle (θ) between the laser and the arc are shown in Fig. 2b. During the welding process, the laser head was tilted 6° along the welding direction to avoid back reflection and potential damage to the equipment, and the metal active gas welding was carried out in pulsed mode. The two HLAW procedures adopted the same welding parameters.

The backing welding procedure was carried out to test the following four major DSHW variables: leading mode, laser power, arc current, and welding velocity. The constant backing welding parameters are shown in Table 3. The leading modes used were the arc leading the laser mode and the laser leading the arc mode. The various laser powers were 2.7 kW, 3.7 kW, and 4.7 kW. The various arc currents were 200 A, 220 A, and 240 A. The various welding velocities were 1400 mm/min, 1000 mm/min, and 600 mm/min. The optimised welding parameters of the DSHW are shown in Table 4. Additionally, DSAW was carried out with an

Table 3
Constant backing welding parameters of double-sided hybrid laser-arc welding.

Laser power (kW)	Arc current (A)	v (mm/min)	Defocus length (mm)	D (mm)	α (°)	β (°)	θ (°)
4.7	220	600	−12	4	15	15	45

Table 4
Optimized welding parameters of double-sided hybrid laser-arc welding.

Pass number	Laser power (kW)	Arc current (A)	Arc voltage (V)	v (mm/min)	Defocus length (mm)	D (mm)	α (°)	β (°)	θ (°)
1	4.7	220	24.4	600	−12	4	15	15	45
2	1.9	238	24.3	800	−8	4	10	10	45
3	1.9	218	23.1	800	−5	4	10	10	45
4	1.9	219	24.2	800	−2	4	10	10	45

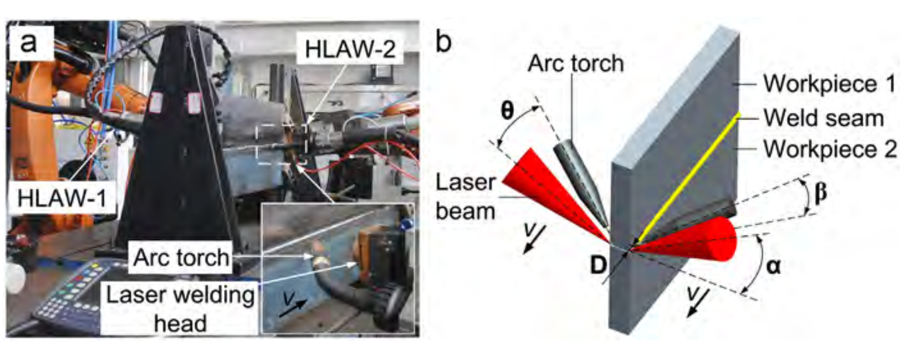

Fig. 2. Double-sided hybrid laser-arc welding system: (a) equipment and (b) schematic.