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Microstructure and performance of hybrid laser-arc welded 40 mm thick 316 L steel plates

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ABSTRACT

Full penetrated welded joint (WJ) without visible flaws were obtained under the optimized welding process. Owing to the inhomogeneous distribution of the chemical elements, the fusion zone (FZ) solidified as first δ-ferrite under the F-A solidification mode in most area and first γ-austenite under the A–F or A solidification mode in the remaining local area. Various temperature histories from the lower layer to the upper layer lead to different degrees of grain growth and phase transformation within the FZ, which subsequently influenced the performance of the WJ. Hardness of the weld center decreased from the lower layer to the upper layer while the tensile properties deteriorated from the lower layer to the upper layer. Different mechanical properties between different layers were considered to be closely related to the growing grain sizes from the lower layer to the upper layer. All tensile specimens failed at the weld zones with massive dimples distributing on the fracture surfaces, indicating a characteristic ductile fracture. The rapid cooling rate inhibited the transition from the high-temperature phase (δ-ferrite) to the low-temperature phase (γ-austenite), which lead to the δ-ferrite content increase within the FZ and weakened the corrosion resistance of the WJ.

1. Introduction

Joining of the construction steel with plate thickness larger than 30 mm is a critical and essential process in manufacturing large-scale marine equipment. Plenty of 316 L stainless steel structures are adopted in these structures and the common used welding technology is the traditional multi-pass multi-layer arc welding. However, owing to the low welding efficiency, large welding deformation and poor welding quality, it is more and more difficult for the traditional welding technology to completely meet the growing manufacturing requirements, as introduced by Reisgen et al. (2016). The emerging welding methods such as narrow-gap arc welding (NGAW), electron beam welding (EBW), autogenous laser welding (ALW) and laser welding with filler wire (LWFW) provide new approaches to thick plate welding. Xiao et al. (2015) realized the joining of the AISI 316LN ASS plate with 100 mm thickness by using double-side multi-layer NGAW process and Yamazaki et al. (2014) joined the JIS G3106 SM490A steel with 40 mm thickness by multi-layer laser welding with filler wire. However, the welding efficiency of the NGAW and the LWFW were both less than satisfactory because of the shallow welding penetration and slow welding speed. In addition, Buddu et al. (2014) reported that the 316 L stainless steel butt joint with 60 mm thickness could be welded by using single-pass EBW process and Bachmann et al. (2014) found that the 304 stainless steel with 20 mm thickness were able to be connected by single-pass high power ALW process. Although the welding penetration and efficiency of the EBW and ALW were much better than that of the NGAW, the required vacuum environment, poor gap adaptability, brittle phase formation and restricted welding thickness by the beam power greatly limited the development of the thick plate welding in the related industries, as introduced by Vollertsen et al. (2010).

The narrow-gap hybrid laser-arc welding (NGHLAW) combined the NGAW with the ALW and the two heat sources interacted in such a way to produce a single high intensity energy source when placed in close contact with each other, as introduced by Wahba et al. (2015). DebRoy et al. (2009) reported that the synergistic interaction of the two heat sources has been shown to overcome problems commonly encountered in each individual welding process. Thus, the NGHLAW technology possessed of advantages including deep penetration, high welding speed, good gap adaptability and unrestricted welding thickness by laser power, which showed enormous potentials to improve the efficiency and quality of the thick plate welding. Ruoyang et al. (2014) successfully made the Q235 steel butt joint with 30 mm thickness by combining the ALW with the LWFW and the NGHLAW, but failed to analyze the microstructure of the Zhen et al. (2014) joined the 16 mm

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Table 1
Chemical compositions of BM and FM (mass fraction: %).

	Cr	Ni	Mo	Mn	Si	P	C	S	Cu	N	Fe
BM	16.82	9.84	1.78	1.52	0.50	0.03	0.02	–	–	–	Bal.
FM	18.12	11.70	2.55	1.86	0.76	0.02	0.01	0.01	0.08	0.05	Bal.

S355J2 W steel by using three-layer NGHLAW process and observed the microstructure of the laser zone, the arc zone and the heat affected zone (HAZ), respectively. Zhang et al. (2017) successfully connected the 40 mm thick mild steel by nine-layer NGHLAW process and studied the microstructure of the laser zone and arc zone. However, the existing research mainly focused on the technical realization of the thick-plate joint and the microstructure of particular positions including laser zone, arc zone and HAZ. No attention has been paid to the microstructural inhomogeneity of the WJ along the thickness direction and its influences on properties of the WJ.

In order to promote the application of the NGHLAW technology, the 316 L austenitic stainless steel butt joint with 40 mm thickness was joined by the multi-layer NGHLAW process. The microstructure, mechanical properties and corrosion behaviour of the WJ were further investigated to illustrate the relationship between the welding process, microstructure and performance of the WJ.

2. Experimental procedure

The base metal (BM) used in this study was 316 L austenitic stainless steel with dimensions of 250 mm × 150 mm × 40 mm and the filler metal (FM) was ER316LSi with a diameter of 1.2 mm. The chemical composition of the BM and the FM were given in Table 1. The hybrid laser-arc welding system was composed of an IPG Photonics Corporation YLR-4000 continuous wave (CW) solid-state Ytterbium fiber laser system and a Fronius (TransPuls Synergic-4000) welding power supply equipped with an ABB IRB-6400 robot.

A narrow-gap Y-groove was prepared to obtain the full penetrated WJ. As shown in Fig. 1a, the bevel angle was 10°, the root size was 5 mm and the platform at each side was 1 mm. The “laser leading” mode was adopted and the welding head was tilted 5° along the welding direction to reduce the influence of high reflectivity and spatters, as shown in Fig. 1b. The 100% Ar was used as shielding gas with a flow rate of 1.5 m^3/h during the welding process. (Li et al., 2015) reported that the contamination and oxide which contributed to the formation of the interlayer defects such as pores, inclusions and lack of fusions could be effectively cleared up by laser cleaning method. Thus, the laser cleaning was used to replace the traditional cleaning process in this study and the detailed parameters were presented as follows: the laser power was 500 W, the pulse repetition rate was 100kHZ, the defocusing amount was 0 mm and the cleaning speed was 1.2 m/min.

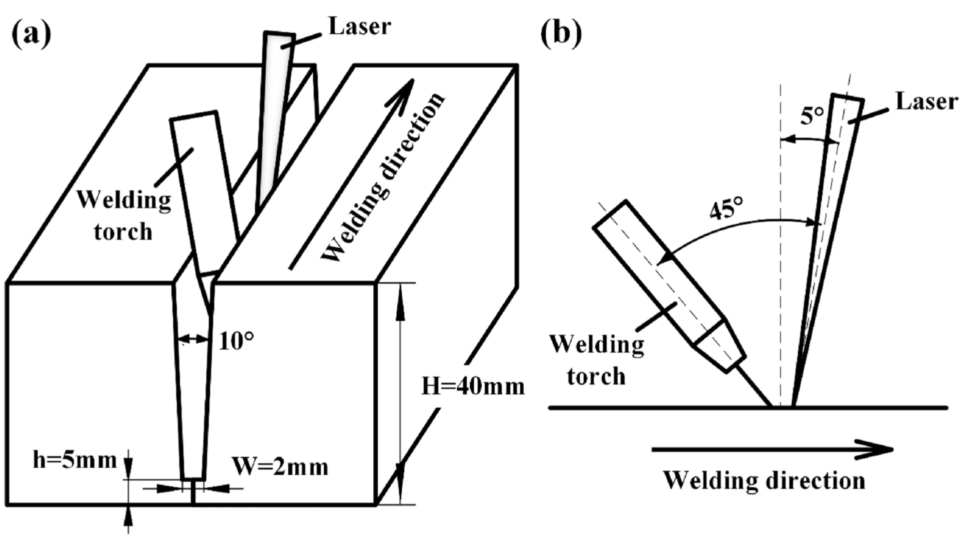

Fig. 1. Schematic of: (a) the groove, (b) the welding process.

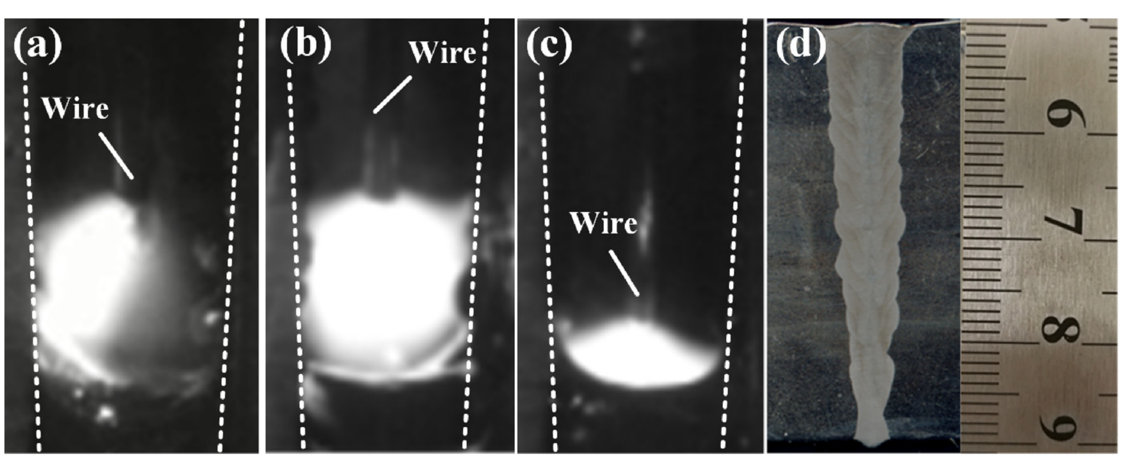

Fig. 2. High speed photography of: (a) deflection of the arc, (b) arc burning up, (c) stable welding process and (d) the cross-sectional morphology.