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Review

Effects of relative positioning of energy sources on weld integrity for hybrid laser arc welding

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A B S T R A C T

This study is concerned with the effects of laser and arc arrangement on weld integrity for the hybrid laser arc welding processes. Experiments were conducted for a high-strength steel using a 4 kW Nd: YAG laser and a metal active gas (MAG) welding facility under two configurations of arc–laser hybrid welding (ALHW) and laser–arc hybrid welding (LAHW). Metallographic analysis and mechanical testing were performed to evaluate the weld integrity in terms of weld bead geometry, microstructure and mechanical properties. The morphology of the weld bead cross-section was studied and the typical macrostructure of the weld beads appeared to be cone-shaped and cocktail cup-shaped under ALHW and LAHW configurations, respectively. The weld integrity attributes of microstructure, phase constituents and microhardness were analyzed for different weld regions. The tensile and impact tests were performed and fracture surface morphology was analyzed by scanning electron microscope. The study showed that ALHW produced joints with a better weld shape and a more uniform microstructure of lath martensite, while LAHW weld had a heterogeneous structure of lath martensite and austenite.

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1. Introduction

The hybrid laser arc welding process combines the highly focused intensity of a laser with the joint filling capability of gas metal arc welding (GMAW). The process usually results in a very narrow heat-affected zone (HAZ) with deep penetration and high travel speeds relative to traditional processes. It provides a unique opportunity for thicker welds with less filler metal or higher travel speeds than typical welding, and hence has been widely implemented in various industrial applications from shipbuilding to automobile production.

The positioning arrangement of the two heat sources in the welding direction plays a critical role in the hybrid laser arc welding process. There are two basic configurations, namely, the

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laser-leading hybrid process with the laser beam preceding the arc [1–3] and the arc-leading hybrid process with the arc preceding the laser beam [4–8]. Extensive research has been done to investigate these hybrid welding processes. To optimize the process stability, weld profile and weld penetration, research work in [5–7] studied the effects of welding parameters such as distance between laser beam and arc (D_{LA}), focused position of laser beam, arc voltage and welding current, laser power, shielding gas composition and the shielding gas flow. Spatters can be generated on the surface of the weld if the parameters are not appropriately chosen. Li et al. [9] investigated the coupling of a Nd:YAG laser beam and a metal inert gas (MIG) arc with the spectrum of the plasma. Their results showed that the laser–MIG hybrid welding processes caused the plasma energy to focus on the center of the welding arc and plasma has stronger radiation intensity near the welding pool. Zhou and Tsai [10] developed mathematical formulas and a numerical solution to investigate the complicated transport phenomena during the spot hybrid laser–MIG welding process. They found that weld pool dynamics, cooling rate, and final weld bead geometry were strongly affected by the impingement process of the droplets. Gao et al. [11] proposed a mathematical model by coupling the laser beam and arc functions into the plasma width and simulated the weld pool development and dynamic process in stationary laser–MIG hybrid welding. They evaluated the transient weld pool shape and complicated liquid metal velocity distribution from two kinds of weld pools to a unified weld pool.

Research has been done to understand the interactions of the two heat sources with different energy distributions during the laser–arc hybrid welding process. Kah et al. [12] studied how the relative positioning of the different sources in laser–arc hybrid welding affected the overall weld quality and penetration depth. Their analysis was based on research results of various studies carried out by different research groups. Casalino et al. [13] investigated arc leading versus laser leading during the hybrid welding of aluminum alloy. Their results showed that the laser-leading configuration produced a better penetration and sounder weld. The laser-leading configuration was found to be more convenient with respect to the arc leading one. For the arc-leading a lower penetration was found to require speed slowdown for deeper penetration. Cao et al. [14] investigated hybrid laser arc welding of thick section high strength low alloy steel. Their results showed that the laser-leading hybrid welding process can produce higher quality welds due to less underfill and porosity defects than arc-leading welding. Wang et al. [15] investigated the effect of the welding direction on the plasma and metal transfer behavior of hybrid welding processes. They found that the temperature and electron density distribution exhibited a bimodal behavior in the case of arc-leading mode, which did not exist in the case of laser-leading mode. They found that the arc-leading mode led to a longer time to generate a drop, while the laser-leading mode reduced the required voltage for the same current.

From the above discussion, it is obvious that the strong coupling effect between laser beam and arc affected the weld thermal cycle and the flow of molten pool of hybrid welding thus the microstructure and the mechanical properties of weld joint. Nonetheless, the effects of the relative positioning of laser beam with arc on the microstructure and mechanical properties during laser–arc hybrid welding were rarely studied in literature according to the authors' best knowledge.

In this work, two configurations of arc–laser hybrid welding process (ALHW) and laser–arc hybrid welding process (LAHW) are experimentally investigated. The effects of the relative positioning of laser beam with arc on the weld bead geometry, microstructure and mechanical properties of weld joints are experimentally analyzed in details for hybrid laser–arc welding.

2. Experiments

2.1. Hybrid welding experiments

The base material used in the welding experiments was a low alloy high-strength steel (HSS), which was cut into $400 \times 100 \times 6.6$ mm coupons. The filler wire was made of an austenitic stainless steel (ASS) with 1.2 mm in diameter. The compositions of the base metal and the filler wires were determined by an ARL 4460 Metals Analyzer as shown in Table 1. Before welding, the specimens were chemically cleaned with acetone to eliminate any surface contamination. These hybrid welding experiments were conducted to obtain a full penetration of 6.6 mm thick HSS specimens for a butt weld configuration with a Y-groove preparation. The weld specimen geometry is schematically described in Fig. 1.

Fig. 2 shows the experimental system for the hybrid welding experiments, which used a 4 kW Nd:YAG laser (Model HL4006D by TRUMPF) in conjunction with a power supply (Model YD-350A G2HGE by Panasonic). The laser operated in the continuous wave (CW) mode with a wavelength of 1.06 μm. During the experiments, the laser beam was focused to a spot of 0.5 mm in diameter on the top surface of the specimen by a fixed focus lens with a focal length of 220 mm. The shielding gas for the arc torch comprised of carbon dioxide (5%) and argon (95%) was delivered at a flow rate of 16 L/min. The welding experimental parameters are given in Table 2. Two experimental configurations of arc-leading ALHW and laser-leading LAHW processes, as illustrated in Fig. 3, were investigated in this study to evaluate the relative positioning of energy sources on the weld integrity.

2.2. Metallographic analysis and mechanical testing

To carry out the metallographic analysis, the weld specimens were firstly sectioned and polished with suitable abrasives and a diamond paste. The specimens were then etched with a 10% oxalic acid to reveal the fusion zone and increase the contrast from the base metal. The microstructure of the weld bead was analyzed using an optical microscope (OM) and a scanning electron microscope (SEM, Model JEOL JSM-6510 LA). In order to detect various phase constituents present in the weld fusion zones, a micro-zone X-ray diffraction (XRD) analysis was carried out at different locations of the welds. The X-ray diffractometer (Model

Table 1
Chemical compositions of HSS and ASS (wt%).

Materials	Chemical composition (wt%)									
	C	Cr	Ni	Mn	Mo	Si	Cu	S	P	Fe
HSS	0.22	0.60	0.95	1.40	0.50	0.28	0.32	0.008	0.002	Bal.
ASS	0.09	21.12	9.14	1.60	0.37	–	–	0.01	0.02	Bal.

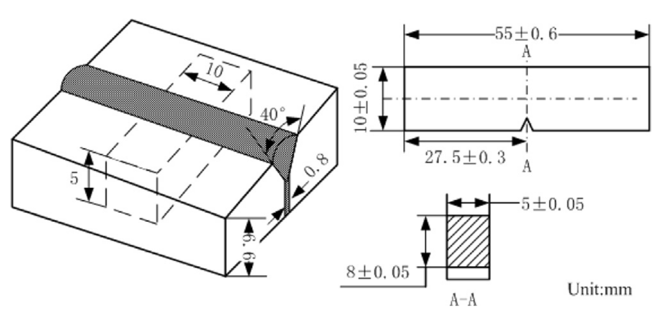

Fig. 1. Schematic of groove shape used in this work.