Journal of Materials Processing Technology 214 (2014) 2823–2833

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Hybrid laser-arc welding of advanced high-strength steel

Wei Liu, Junjie Ma, Guang Yang, Radovan Kovacevic*

Center for Laser-aided Manufacturing, Southern Methodist University, 3101 Dyer Street, Dallas, TX 75205, USA

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form 25 June 2014
Accepted 26 June 2014
Available online 5 July 2014

Keywords:
Hybrid welding
Synergetic effect
Metal transfer mode
Porosity
On-line monitoring

ABSTRACT

This study investigated the synergetic effect between laser beam and electrical arc during hybrid welding by using a spectral diagnostic technique. The synergetic effect increased the energy density in the keyhole and deepened the weld penetration, resulting in a lower plasma electron temperature. The metal transfer mode was a globular one at a small offset distance while a spray mode was achieved with an increase in the offset distance. The decrease in the arc voltage and arc current due to the synergetic effect caused this transition from spray to globular modes. Globular transfer mode destabilized the molten pool and keyhole with the large droplet impingement, leading to the formation of porosity in the corresponding weld bead. The presence of porosity was on-line detected by identifying serious fluctuations in the Fe I electron temperature signals based on the fact that the instability of the molten pool and keyhole is strongly related to the signals coming from the plasma.

1. Introduction

Hybrid laser-arc welding (HLAW) takes advantage of deeper weld penetration and higher processing speed of the laser beam, while the arc and the selected filler wire relax the restricted setup requirement, adjust the metallurgical and mechanical properties, and improve the weld quality. With respect to multi-pass traditional arc welding of thick steel plates, more material and time are saved by using HLAW. Morey (2014) reported that HLAW has been an important modern joining approach and is widely applied in fabrication industries as a result of the maturity of solid-state laser technology.

Jokinen and Karhu (2003) utilized HLAW to weld 20-mm thick austenitic stainless steel plates and found that the crucial factor for achieving sound welds was the offset distance between the filler wire and laser spot at the top surface of the workpiece. Naito et al. (2002) welded Type 304 stainless steel plates by using laser beam assisted by an arc. They mentioned that an increase in laser power was more effective in deepening the weld penetration than the arc power. Cao et al. (2011) welded 9.5-mm thick HSLA-65 steel plates using HLAW in one pass. They achieved a weld with better quality when the laser beam was in a leading position. Cao et al. (2006) reported that a deeper weld penetration was achieved when a laser beam was focused under the workpiece surface. Qin et al. (2007) studied the effect of arc power onthe weld-bead dimensions. They found that with an increase in the welding current, the weld penetration deepened due to an increase in the arc force acting on the molten pool. However, Nielsen et al. (2002) pointed out that the weld penetration was reduced when the keyhole was disturbed by the addition of too much filler wire. Makino et al. (2002) investigated the effect of welding current waveform on the stability of the HLAW process. The result showed that the pulsed welding current produced a better weld quality with respect to the continuous current mode. Campana et al. (2007) presented that a pulsed-spray metal transfer mode was preferred to achieve a stable hybrid-welding process with respect to a short-circuit/globular mode.

Chen et al. (2006) found that there were two welding mechanisms in HLAW, keyhole heat absorption model and surface heat flux absorption model. The formation of a keyhole is the key to conduct deep penetration welding. Hu and Den Ouden (2005) modified the Rosenthal equation to calculate the ratio of heat input transferred into the workpiece. They reported a higher melting efficiency in HLAW as a result of the usage of two heat sources and the contraction of the arc. Tusek and Suban (1999) found that a stable electrical arc and a decrease in the arc voltage were achieved in HLAW because of the interaction between laser beam and arc. Gornyi et al. (1990) presented that the arc voltage decreased only when a keyhole was achieved, characterized by ionized atoms and ions from the vaporized material. Liu and Chen (2011) investigated the plasma characteristics of HLAW. The interaction between laser beam and arc was reflected in the variation of the plasma electron temperature. Wang et al. (2011) analyzed the plasma characterization during the hybrid laser-arc welding by the spectroscopic signals.

---

* Corresponding author. Tel.: +1 214 768 4865; fax: +1 214 768 2116.
E-mail address: kovacevi@lyle.smu.edu (R. Kovacevic).

http://dx.doi.org/10.1016/j.jmatprotec.2014.06.018
0924-0136/

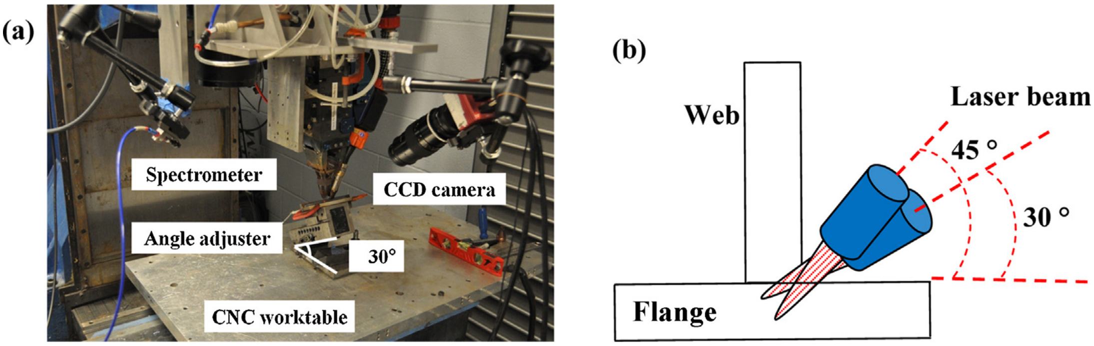

Fig. 1. (a) Experimental setup of hybrid laser-GMA welding system; (b) positions of the laser beam running through the T-joint configuration.

Previous studies on the synergetic effect between laser beam and electrical arc focused on the effects of welding parameters, such as offset distance, welding current, scanning speed, and metal transfer mode, on the weld-bead dimensions and the stability of the welding process. The fundamental principles of the synergetic effect were not well understood. In this work, the synergetic effect between laser beam and electrical arc was investigated by using a spectral diagnostic technique assisted by a high-speed charge-coupled device (CCD) camera. The spectrometer was used to study the plasma characteristics of the hybrid laser-arc welding. The CCD camera was applied to visualize the welding process and monitor the interaction between laser beam and arc. The welding current and the offset distance were varied to study their effects on the weld-bead shape, the stability of the welding process, and the plasma characteristics.

2. Experimental procedure

Fig. 1 shows the experimental setup of a hybrid laser/gas metal arc (GMA) welding system that includes a laser head, a GMA power source, and a monitoring system consisting of a high-speed CCD camera and a spectrometer. The laser head was connected to a continuous-wave fiber laser with a maximum power of 4 kW. A collimating lens of 150 mm and a focusing lens of 250 mm were selected to obtain a laser focusing spot of 0.6 mm. The optical emission spectrum in the plasma plume located above the molten pool was detected using the spectrometer with a wavelength resolution of 0.4 nm and a slit width of 50 μm.

High-hardness martensitic advanced high-strength steel (AHSS) plates were used in this work. The steel was quenched and tempered at very high temperature. Essar Steel Algoma Inc (2008) provided the chemical compositions of AHSS, as shown in Table 1. The 8-mm thick AHSS in a T-joint configuration were welded by using the hybrid laser-GMA welding station. The size of the T-joint configuration is presented in Fig. 2a. ER70S-6 was used as the filler wire with 1.5 mm in diameter.

Before welding, the samples were brushed to remove the residue and scale from the surface by a wire brush, and degreased by the acetone solution. The plates were clamped to an angle adjuster that was positioned at 30° with respect to the surface of the computer numerical control (CNC) worktable. As shown in Fig. 1b, under a 30° work angle, the laser beam will pass through less material in the flange in order to obtain the full penetration of the fillet weld along the thickness direction of the web. The consumption of laser power was correspondingly smaller than in the case of a 45° work angle. The CCD camera was also tilted 30° in order to place the CCD camera and the web of the T-joint in the same surface area. In order to minimize the distortion of the samples during welding, both ends of the T-joint were clamped to the fixture and tack-welded.

Preliminary tests were conducted to determine the final welding parameters shown in Table 2. The offset distance in this work was the distance between the laser beam focal point and the filler wire tip at the intersection line between the flange and web. The welding current and the offset distance were varied to study their influence on the hybrid laser-GMA welding process. A "SYNERGY" function was used to select the GMA welding parameters. For a certain wire feeding rate, the CLOOS GMA power source matched an optimum welding current. The filler wire feeding rate was proportional to the welding current. The focal point of laser beam was set 1 mm below the workpiece surface. The laser-leading direction was selected. The feeding wire was positioned at 70° with respect to the horizontal surface of the CNC worktable. Argon was supplied

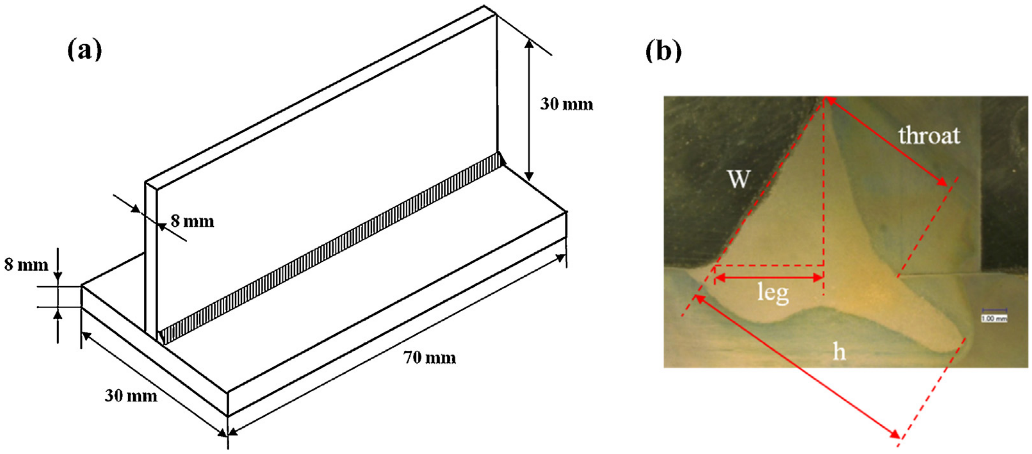

Fig. 2. (a) Geometry and size of the T-joint configuration; (b) schematic diagram of parts of a fillet weld.