Optics and Lasers in Engineering 92 (2017) 39–47

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

# Analysis of plasma characteristics and conductive mechanism of laser assisted pulsed arc welding

Shuangyu Liu[a], Shixian Chen[a], Qinghua Wang[b], Yanqing Li[a,*], Hong Zhang[a], Hongtao Ding[b]

[a] College of Mechanical and Electrical Engineering, Changchun University of Science and Technology, 7089 Weixing Road, Changchun 130022, PR China
[b] Department of Mechanical & Industrial Engineering, University of Iowa, Iowa City, IA 52242, USA

ARTICLE INFO

*Keywords:*
Hybrid laser-arc welding
Plasmas
Spectrum
High nitrogen steel

ABSTRACT

This study aims to investigate the arc plasma shape and the spectral characteristics during the laser assisted pulsed arc welding process. The arc plasma shape was synchronously observed using a high speed camera, and the emission spectrum of plasma was obtained by spectrometer. The well-known Boltzmann plot method and Stark broadening were used to calculate the electron temperature and density respectively. The conductive mechanism of arc ignition in laser assisted arc hybrid welding was investigated, and it was found that the plasma current moved to the arc anode under the action of electric field. Thus, a significant parabolic channel was formed between the keyhole and the wire tip. This channel became the main method of energy transformation between the arc and the molten pool. The calculation results of plasma resistivity show that the laser plasma has low resistivity as the starting point of conductive channel formation. When the laser pulse duration increases, the intensity of the plasma radiation spectrum and the plasma electron density will increase, and the electron temperature will decrease.

## 1. Introduction

The laser-arc hybrid welding process combining of a laser and an electrical arc sources has attracted considerable attentions recently due to its unique advantages compared with a single heat source welding [1]. The speed of hybrid welding is quite high and this process can result in deep penetration and good gap bridging. Therefore, it is finding applications in diverse industries like automotive, aerospace, shipbuilding, oil and pressure vessel industries, etc. In addition, it can overcome problems commonly encountered during either laser or arc welding, such as cracking and porosity, thus achieving outstanding mechanical properties [2–4].

The plasma characteristics and conductive mechanism during the laser-arc hybrid welding is a very complicated physical and chemical process involving the interaction between the plasma and the arc. Due to the complexity of hybrid welding and the limitation of testing methods, the coupling mechanism of laser and arc has always been a hotspot for researchers. Li et al. [5] carried out thorough review of the research work on coupling effect of laser with plasma arc and provided some useful information for the coupling mechanisms between laser and arc during the hybrid laser-arc welding process. In recent years, many researchers have studied the characteristics of laser-induced plasma, arc plasma and hybrid plasma and they conducted extensive work on investigating the coupling mechanism of different plasmas for laser-arc hybrid welding. Wang et al. [6] captured the plasma images from different welding processes (Laser only, MIG only, and Laser-MIG hybrid) using a high speed camera. The experimental results showed that a curved channel was formed between the filler material and keyhole during the hybrid welding process. The spectral intensities of the metal and shielding gas elements for the MIG-only welding and laser-MIG hybrid welding processes are significantly different. Kutsuna and Chen [7] performed laser-MAG hybrid welding experiments to investigate the effects of process parameters on penetration depth and the interaction between laser plasma and MAG arc plasma. The results indicated that the penetration depth of hybrid welding is higher than those of laser or MAG welding only due to the laser plasma deflected towards the arc plasma which reduces the amount of laser energy loss. Liu and Chen [8] examined the shape, electron temperature and electron density of hybrid plasma during laser-arc hybrid welding. It was found that the distance between tungsten electrode and laser will influence the interaction between the laser and the arc. In addition, the electron temperature increases and electron density decreases when the keyhole is directly under the arc plasma due to the expansion caused by keyhole vapor colliding with the arc plasma. Möller and Thomy [9] observed that the laser beam influences plasma arc during the laser-arc hybrid welding of aluminum. The laser-induced aluminum vapor

* Corresponding author.
*E-mail address:* liushuangyu@cust.edu.cn (Y. Li).

http://dx.doi.org/10.1016/j.optlaseng.2016.12.016
Received 12 August 2016; Received in revised form 15 December 2016; Accepted 19 December 2016
Available online 23 December 2016

increases the conductivity of medium in the plasma arc and decreases of the plasma voltage. The arc becomes stable if the laser or plasma removes the oxide layer on the aluminum surface. Gu et al. [10] investigated the physical interaction between the laser and arcs during laser-twin-arc hybrid welding process and analyzed the influence of the laser/arc heat source on the welding process. The experimental results indicated that the laser builds a conductive channel for the arcs that will affect the arc shape and stabilize the arc. The electron temperature will be significantly influenced by laser parameters.

Besides the plasma characteristics and coupling mechanism, some researchers also investigated other issues associated with laser-arc hybrid welding, such as radiation of plasma and conductive mechanisms during laser-arc hybrid welding, and obtained some very useful results. Li et al. [11] investigated the radiation of laser-MAG hybrid welding plasma with fiber spectrometer. The result showed that there is a high radiation intensity zone with larger gradient in the center of laser-arc hybrid welding plasma. The laser-arc hybrid welding process will cause the plasma energy to focus on the center of welding arc and the welding pool. Mahrle et al. [12] suggested that the primary interactions should not be considered as driving mechanism for beneficial effects such as increased stabilization and penetration depth during the hybrid laser-arc welding process. Based on the experimental results and numerical analysis, it is believed that laser sources with specific wavelength can achieve the beneficial effects therefore secondary interactions have stronger impact in hybrid laser-arc welding processes. Stute et al. [13] concluded that the electric arc is stabilized by several physical effects during the hybrid welding with a laser/TIG system. The laser provides a channel of increased conductivity to realize the stabilization for the arc, which can be used to achieve more flexible and efficient plasma processes.

Although researchers have extensively conducted research work on the coupling mechanisms between laser plasma and arc plasma during laser-arc hybrid welding, the understanding of plasma characteristics and conductive mechanism is still very limited due to the lack of thorough investigation on how the laser and arc interacts from the perspective of process physics and how the conductive channels are formed during laser-arc hybrid welding. In order to further investigate the physical mechanism between laser and arc, the high speed camera and the spectrometer were simultaneously used to obtain the in-situ and accurate information of the arc shape and the emission spectrum of plasma between the pulse laser and arc hybrid welding respectively in this work. Based on the information provided by the captured images and emission spectrum of arc plasma, the plasma resistivity and electron temperature and density were calculated. The calculation results were then used to reveal the conductive mechanism between the pulse laser and arc during laser-arc hybrid welding process.

## 2. Experiments

The experimental setup for the pulsed laser-MAG hybrid welding process is shown in Fig. 1, which mainly consists of a 2.5 kW Nd: YAG solid state laser (model HL4006D by TRUMPF) and a pulse metal active gas (MAG-P) welding system (model YD-350A G2HGE by Panasonic). The Nd: YAG laser was operated in the rectangular pulse mode with a wavelength of 1.06 μm. Various laser pulse durations ranging from 10 to 30 ms were experimentally investigated in this study. During the experiment, the laser beam was focused using a fixed focus lens with a focal length of 220 mm. By placing the sample-material top surface 2 mm above the focal point ($\Delta f = -2$ mm) the spot diameter of 0.46 mm was achieved. The spot diameter was measured by the beam quality analyzer (model Focus Monitor 120 by PRIMES). A waveform control logic was applied to the MAG-P welding system to produce a precise control of the arc with a waveform frequency of 100 Hz. The matching of the output pulse signal of the welding machine and the laser is realized by using the synchronous signal and the time delay processes. The shielding gas for the arc torch composed of Carbon Dioxide (10 vol%) and Argon (90 vol%) was delivered at a volume flow rate of 17 L/min. The welding experimental parameters are given in Table 1.

The base metal plates used in the experiments were made of a high-nitrogen austenitic stainless steel with a dimension of $150 \times 30 \times 8$ mm. Before the welding experiment, the base metal plate surfaces were chemically cleaned by acetone to eliminate any surface contamination. Austenitic stainless steel filler wire with 1.2 mm in diameter was used in the experiments. Table 2 shows the chemical compositions of both base metal and filler wire materials.

The welding arc shape and metal transport phenomena were recorded during the experiments using a CMOS high speed camera (model CR5000 × 2 from Optronis) operating with a framerate of 4000 fps at full resolution. To collect shape of arc, a LD pumped green laser was used as backlight source. The LD pumped laser with an emission wavelength of 532 nm can deliver in continuous wave (CW) mode. The interference filter with wavelength of 532 nm was installed in front of high speed camera for filter out most of the arc light, which is show in Fig. 1(a). The high speed camera-1 was placed on the side of the hybrid welding head and the angle between the high speed camera and the Y direction is 150° in YZ plane, and equipped with a fast Gigabit ethernet connection to transfer the previously captured high-speed image sequences to computer. The high speed camera-2 was used to capture droplet. A welding process analysis and monitoring system (model Analysator Hannover developed by University of Hanover, Germany) was used to measure and statistically process the on-line electric signals of the MAG-P welding system.

Arc light emission was monitored using a spectrum acquisition system as shown in Fig. 1(b) and Fig. 2, which consists of a set of optical lens, an imaging receiving module, a quartz optical fiber image transmitting bundle and a position adjusting mechanical component. A 1:1 real image is formed on the receiving screen of the image receiving module d by the radiation light of plasma arc which travels through zoom lens a, plus lens b and dimmer glass c. The image receiving module consists of receiving screen d and fiber probe e. An image capture hole with 3 mm in diameter was drilled at the centerline of the receiving screen by wire-electrode cutting. The fiber probe was placed inside the image capture hole. The radiation light of the electrical arc was transmitted into the inlet slit of the spectrograph through the receiving screen using the quartz optical fiber image transmitting bundle. The sketch of the experimental setup is shown in Fig. 1(b).

- During the experiment, the fiber optic probe was positioned 1.5 mm and 1 mm away from the sample surface and laser beam respectively by adjusting the three micrometer positioning stages.
- Light emitted from the arc plasma plume formed a life-size inverted image through an imaging lens.
- The collected light signals were transmitted to the spectrometer by an optical fiber.

## 3. Results and discussions

### 3.1. Effect of laser plasma on arc plasma shape and spectral signal

The coupling principles between the arc pulse period and laser pulse period are shown in Fig. 3. When combining a pulsed laser with pulsed arc, there are 4 phases existing within one period: (1) Pure laser; (2) Hybrid phase with arc and laser; (3) Idling with no arc and laser; and (4) Pure arc. One period is actually 20 ms with all 4 phases mixed together. One of the typical coupling form is the coupling between the arc pulse period and laser pulse base value (APLB) in which only arc pulse exists, as shown in Fig. 3. The other typical coupling type is the coupling between the arc pulse period and laser pulse peak value (APLP) in which both arc pulse and laser pulse exist, as shown in Fig. 3. The arc shape was compared between the two coupling forms. The base