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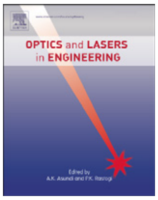

Effect of laser pulse on recovery delay of arc plasma based on ion migration behavior in the pulsed laser–arc hybrid welding process

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ABSTRACT

This paper presents the investigation on effect of laser pulse on the recovery delay of arc plasma during pulsed laser–arc hybrid welding of Mg alloy based on the dynamic behavior of Mg atoms. High-speed camera and spectrograph are employed to monitor the behaviors of Mg atom in the arc plasma and to characterize the effect of laser pulse on the arc plasma, respectively. It is found that the arc plasma cannot recover to its original state immediately after laser pulse action and it takes 0–5 ms for the excessive Mg atoms to escape from the arc plasma depending on the given parameters. According to the calculation, time for Mg ions to travel from the anode to the cathode in the conduction channel of the arc plasma is less than 0.1 ms. The high temperature of the laser keyhole region on the base material surface still exists when the laser pulse is removed and sustaining supply of the Mg ions from this region is the essential factor influencing recovery delay of the arc plasma.

1. Introduction

Hybrid laser–arc welding, conducted firstly by Steen in 1979 [1], is noticed as a promising joining process since it can compensate for the drawbacks or weaknesses in laser welding and arc welding by utilizing both features [2–6]. Now, much attention has been paid to this new welding method and, a lot of work has been done mainly on the development of this technique and expanding its applications [7–11]. While, further development of this method needs deeper understandings about the interactions among the laser, the arc plasma and even the materials being processed. But, essential mechanism, especially the effect of laser radiation on intrinsic characteristics of the arc plasma, still remains unclear, which is the largest obstacle for further development of this manufactory technique.

According to existing reports, there is little direct interaction between the laser and arc plasma in the plasma space, including strong absorption, reflection and deflection, due to the fact that the electron density of the welding plasma is not high enough (at the grade of 10^{16}–10^{17} cm^{-3}) to influence the laser radiation heavily with the wavelength ranging from 10^2–10^4 nm [12]. Actually, compared with laser radiation, characteristics of arc plasma vary intensively during the hybrid process and influences of laser radiation on the arc plasma mainly come from the laser-affected material, such as the laser keyhole in the base material, laser-induced plume over the base material surface and the laser-induced plasma inside the keyhole [13]. Researchers have already noticed that during laser–arc hybrid welding, atoms of the base material will move into the plasma column replacing a part of the original atoms (e.g. Ar atoms) to ionize and conduct electricity, which essentially changes the characteristics of the plasma, such as composition, ionization degree, electron temperature and density [13,14]. This will directly result in the variation of the energy, density and stability of arc plasma. As one of the main parts of the hybrid heat source, arc plasma dominants the energy distribution of the entire heat source, and the variation of its features will directly lead to the change of heating ability and manufacturing results, which is mostly concerned by the researchers. However, the literature focusing on this point is extremely limited.

In this study, the dynamic behavior of base material atoms in the welding plasma is aimed at to indirectly investigate the interactions between laser and arc plasma and their synergistic effects. By monitoring behaviors of arc plasma during and after laser pulse action, the influence of the laser pulse on the arc plasma can be presented easily and clearly. With the help of high-speed camera, narrow-band filters and high-resolution spectrometer, the distribution and light emissions of atoms in the arc plasma can be accurately and real-timely acquired. Accordingly, the behavior of material atoms in the arc plasma can be exposed by the experimental results and corresponding physics theories. It is thought that this study is significant for further understanding the nature of laser–arc hybrid heat source.

2. Experimental setup

As is shown schematically in Fig. 1, the heat source is a pulsed Nd:YAG laser combined with a direct current electrode negative

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(DCEN) arc plasma generated by a gas tungsten arc (GTA) welding machine. The laser, with the wavelength of 1.064 μm, is focused by a lens with a focal distance of 120 mm into a spot measuring about 0.5 mm on the workpiece surface. Throughout this experiment, the defocusing distance of the laser beam is zero, meaning that the laser focal spot is just on the workpiece surface. Accurate control of laser pulse energy can be realized by independently adjusting the pulse duration and the exciting electric current as the functions of the laser source, and a square waveform is adopted here. The value of laser pulse energy can be measured by a special pulse energy meter. According to the values of pulse energy, the pulse duration and the pulse frequency, the laser peak power and average power can be calculated. In this research, rolled AZ31B Mg alloy plate is selected as the base material because of its attractive features, such as low melting point (about 903 K), low boiling point (about 1363 K) and low ionization energy (7.6 eV), which can amplify and clarify the phenomenon. The 6 mm thick plates are used in the bead-on-plate welding experiment to avoid the influence of full penetration, and its chemical compositions are listed in Table 1. The arc electrode with 3.2 mm diameter consists of 98% tungsten and 2% cerium and its tip angle is ground to 30°. There is an adjustable distance between the laser beam axis and the GTA electrode tip (Dla). The angle of GTA electrode axis to the plate is kept 45°. The height of electrode tip from the plate surface is 1.2 mm in the whole welding experiment. Argon with a purity of 99.99% is utilized as the shielding gas and its flow rate out of nozzle is approximately 10 L min^{-1}. After welding, the welding seam is cross-sectioned and etched by an acid solution (5% HCl+95% alcohol) for the observation of welding pool size.

A high-speed camera with the maximum acquiring frequency of 3000 frame s^{-1} is positioned towards the laser acting point and vertically to the welding direction to acquire the side shape of the arc plasma. The spectral information of the welding plasma is characterized by a spectrometer (SP-2556) produced by Acton Company, and corresponding acquiring parameters and data processing method (for calculating the electron temperature and density) can be found in Refs. [13–19]. Meanwhile, according to the welding plasma spectrum and the NIST (National Institute of Standards and Technology) database [15], two narrow-band optical filters were employed for the separate observation of the distributions of Mg and Ar atoms in the plasma (See Fig. 2), and the corresponding parameters for the filters were presented in Table 2.

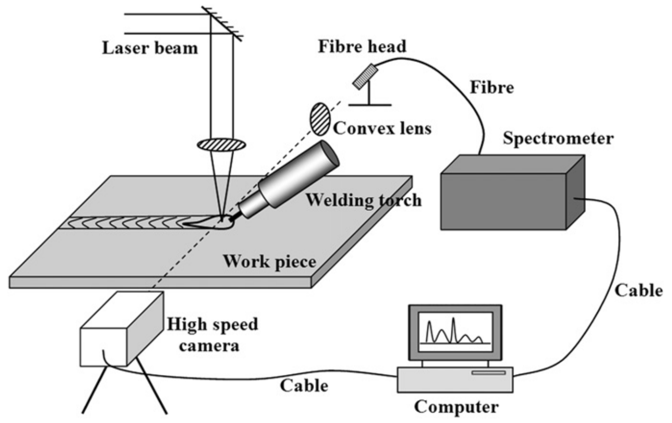

Fig. 1. Schematic diagram of experimental devices.

Table 1
Chemical compositions (wt%) of Mg alloy plate used in experiments.

Alloy	Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
AZ31B	2.5∼3.5	0.7∼1.3	0.2∼1.0	<0.05	<0.01	<0.001	<0.002	Bal.

3. Experimental results

3.1. Effect of laser pulse on arc plasma

By the high speed camera together with the optical filters, behaviors of Mg and Ar plasma during laser pulse action were monitored. Fig. 3(a) gives the positional relationship between laser and arc plasma before the laser pulse action, and Fig. 3(b) presents the welding plasma behaviors during and after laser pulse action. As shown in Fig. 3(b), the volume of Mg plasma expands while that of Ar plasma contracts during laser pulse action, indicating that Mg atoms in arc column become thicker and replace part of Ar atoms to ionize and conduct electricity.

At the same time, it is found that the arc plasma cannot recover to its original state immediately after laser pulse action, meaning that there is a recovery delay of the arc plasma after one laser pulse as shown in Fig. 4. The Mg atoms emit light heavily during laser pulse action, but when laser pulse disappears, flaring Mg atoms separate from the arc plasma gradually. A long Mg plasma flame consisting of Mg atoms can be seen, and fades away with the time. The time, during which the arc plasma returns to its original state, is a direct reflection of the behaviors of the Mg atoms in the arc plasma during and after the laser pulse action.

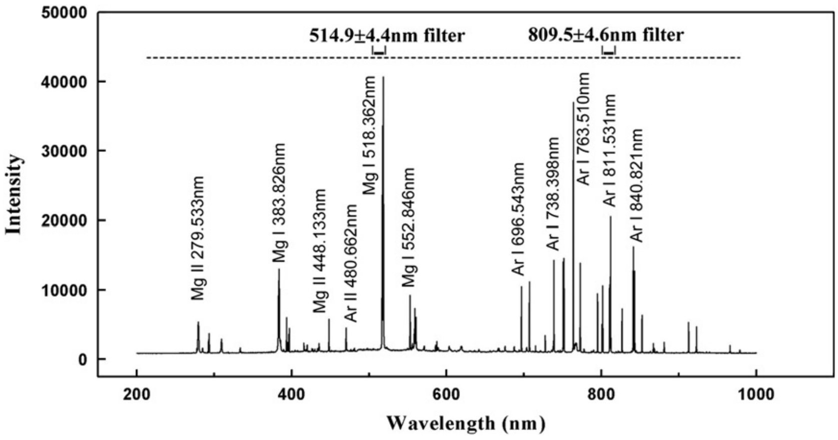

Fig. 2. Spectral lines of arc plasma and narrow-band filter coverage.