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Interaction between laser-induced plasma/vapor and arc plasma during fiber laser-MIG hybrid welding †

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Abstract

Hybrid plasma is an important physical phenomenon in fiber laser-MIG hybrid welding. It greatly affects the stability of the process, the quality of the weld, and the efficiency of energy coupling. In this paper, clear and direct proofs of these characteristics are presented through high-speed video images. Spectroscopic analysis is used to describe the characterization of hybrid plasma. The hybrid plasma forms a curved channel between the welding wire and the keyhole during the fiber laser-MIG hybrid welding process. The curved channel is composed of two parts. The laser-induced plasma/vapor expands due to the combined effect of the laser and the MIG arc, forming an ionization duct, which is one part of the curved channel. The resistance of the duct is smaller than that of other locations because of the rise in electrical conductivity. Consequently, the electrical arc is guided through the duct to the surface of the material, which is the other part of the curved channel. The spectral intensities of metal elements in laser-MIG hybrid welding are much stronger than those in MIG-only welding, whereas the spectral intensities of shielding gas element in laser-MIG hybrid welding are much weaker.

Keywords: Curved channel; Fiber plasma; Hybrid plasma; High-speed video image; Laser-MIG hybrid welding

1. Introduction

Laser-arc hybrid welding technology has received significant attention in recent years because of its advantages, such as its deeper welding penetration, the ability to bridge relatively large gaps, and high welding speed, among others [1-4]. Laser-MIG hybrid welding is one of the most promising processes in the development of a highly efficient and high-quality manufacturing because it overcomes the individual drawbacks associated with the MIG and laser welding processes.

Laser-MIG hybrid welding has been investigated for application in many fields, such as aerospace, motor vehicles, rail cars, shipbuilding, pressure vessels, and oil industries, among others [5-7]. However, previous research has concentrated on the optimization of welding parameters and the improvement of weldability of particular materials [8-12]; only a few studies have been conducted on the mechanisms of hybrid welding. Simulations and statistical analysis have also been used to examine the hybrid welding process [13-14]. Hybrid plasma is an important physical phenomenon in laser-MIG hybrid welding because it greatly affects the stability of the process, the quality of the weld, and the efficiency of energy coupling. The hybrid plasma is composed of laser induced plasma/vapor and arc plasma. Studies on the mechanism of the interaction between laser-induced plasma/vapor and arc plasma provide a theoretical basis for laser-MIG hybrid welding, and promote its practical application.

Steen and Eboo [1] first presented the paraxial CO_2 laser-TIG hybrid welding and observed that the arc rooted preferentially to the laser-generated plasma or hot spot. In the above experiments, the arc was located either on the same side as the laser of the workpiece, or on the opposite side. Ishide et al. [15] described the basic welding phenomena in coaxial TIG-YAG and MIG/MAG-YAG hybrid welding. According to the results obtained through high-speed video images, the arc was pulled in the direction of the keyhole and was fixed at this location. Stute et al. [16] observed the interaction between the YAG laser radiation and the TIG arc. In their experiment, the laser radiation angle relative to the perpendicular direction was 26°; the stabilization and guidance of plasma plumes were also assessed. Chen et al. [17] found that laser could significantly compress and stabilize the arc, and that this compression effect was weakened with the growth of the hybrid plasma. Liu et al. [18] researched the YAG laser-GTAW hybrid welding behaviors of Mg-based alloys. Results obtained by high-speed imaging also indicated that the welding arc rooted to the impinged spot of the laser beam, and that the arc became more stable. In the previous work, due to the high

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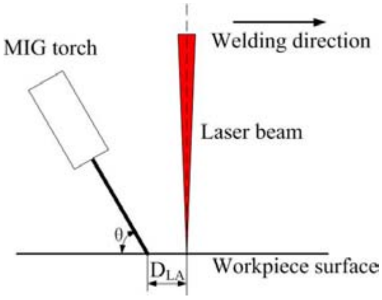

Fig. 1. Schematic of fiber laser-MIG hybrid welding setup.

intensity of the hybrid plasma radiation, the conductive channel from the welding wire to the keyhole was not clearly provided in its entirety. Using spectroscopic measurement, Hu and Ouden [19] found that the composition of the arc plasma during laser-TIG welding changed due to the strong evaporation of the workpiece material. In the present study, this observed change contributes to a better understanding of the interaction between laser-induced plasma/vapor and arc plasma.

Due to the complexity of the physics of the underlying interactions, many fundamental questions need to be addressed. For instance, the composition of the hybrid plasma needs to be ascertained, and how the laser-induced plasma/vapor and arc plasma interact with each other during fiber laser-arc hybrid welding needs to be understood.

In the present paper, high-speed video observation and spectroscopic analysis are used to examine the interaction between laser-induced plasma/vapor and arc plasma during high-power CW fiber laser-MIG hybrid welding. A curved conductive channel between the welding wire and the keyhole is established through clear and direct proof, reflecting the guidance of laser radiation on the arc. The reason for the formation of the curved channel is also discussed.

2. Experiment

The experimental setup used consisted of a 4 kW CW fiber laser (IPG YLR-4000) and TPS4000 digital arc-welder power (Fronius). The schematic of the setup is shown in Fig. 1. The laser beam was delivered through the optic fiber and focused on a spot 0.3 mm in diameter by a 250 mm focal distance lens. The focal point was set on the surface of the workpiece. The separation distance between the axis of the laser focal point and arc electrode tip (D_{LA}) was 4 mm. The torch angle relative to the workpiece surface (θ) was 75°, and the wire extension of the weld torch was 13 mm.

The base material used was ZL114 aluminum alloy plate (8 mm thickness) The wire diameter was 1.0 mm. The chemical compositions of ZL114 and the wire are shown in Table 1.

The plasma images were captured by a high-speed camera (Photonfocus). The spectra of the plasmas were acquired by an Avaspec-2048FT optical fiber digital spectrometer (Avantes). The experimental setup for observation of welding phenomena is given in Fig. 2. Additional illumination from a diode laser was used to obtain a clear image. To reduce the intensity of plasma radiation, optical filters, including both attenuation and narrow-band filters, were placed at the aperture of the camera.

Table 1. Chemical composition of ZL114 and wire (wt%).

	Si	Mg	Cu	Mn	Fe	Ti	Al
ZL114	6.5–7.5	0.45–0.75	0.1	0.1	0.2	0.08–0.25	Bal.
Wire	11.0–13.0	0.3	0.1	0.15	0.8	0.2	Bal.

Table 2. Welding parameters.

	Welding speed	Laser power	Arc current
MIG only	1 m/min		140 A
Laser only	1 m/min	3 kW	
Laser-MIG hybrid	1 m/min	3 kW	140 A

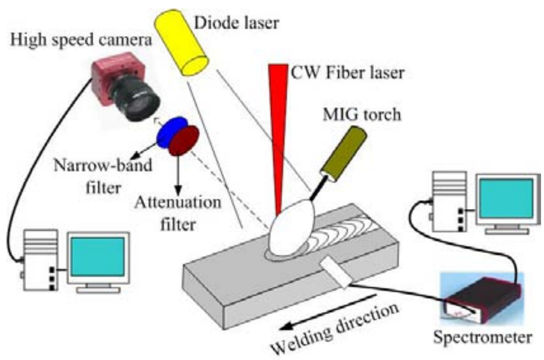

Fig. 2. Schematic of the experimental setup for observation of welding phenomena.

3. Results

The experiments were carried out using bead-on-plate welds. In order to study the interaction between laser-induced plasma/vapor and arc plasma, the processes of laser-MIG hybrid welding used were the same parameters as those of the MIG-only welding and the laser-only welding. The welding parameters are provided in Table 2. The shielding gas used was argon gas at a flow rate of 20 L min^{-1}, coursed directly through the MIG torch.

3.1 Images of plasmas

High-speed video images of plasmas induced during MIG-only welding, laser-only welding, and laser-MIG hybrid welding are shown in Fig. 3. The acquiring frequency of the high-speed camera is 1000 frames s^{-1}; photos were taken at 1 ms intervals.

The brightness indicates the temperature and the energy. The higher the brightness, the higher the temperature, and the greater the energy. Based on the images, the brightness of the plasma induced during laser welding is very weak compared with the other two kinds of plasmas. In Fig. 3(a), the energy of

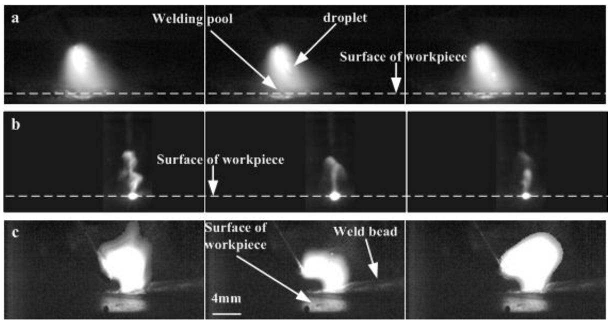

Fig. 3. High-speed video images of plasmas (a) MIG; (b) laser; (c) laser-MIG hybrid welding.

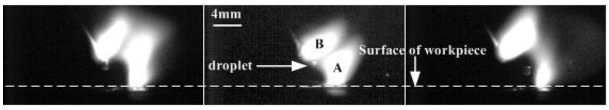

Fig. 4. High-speed video images of plasma induced during laser-MIG hybrid welding.

MIG is distributed mainly in the upper part of the arc (near the welding wire tip); thus, the heat gradually decreases along the wire axis with increasing distance from the welding wire tip. This results in less heat acting directly on the welding pool. In Fig. 3(b), the laser plasma is formed in a columnar zone above the laser-acting position, and its energy focuses on the keyhole and the nearby zone. Fig. 3(c) shows that the hybrid plasma forms a curved channel between the welding wire and the keyhole during the fiber laser-MIG hybrid welding process. The energy of the hybrid plasma does not fluctuate significantly within the channel due to the similar brightness.

In Fig. 3(c), the molten pool is generated in the position irradiated with the laser beam, whereas the arc is rooted to the impinging spot of the laser beam. The laser-MIG hybrid plasma has stronger intensity at the surface near the welding pool. Therefore, the hybrid welding conveys more heat to the welding pool.

To obtain clear images showing the details of the curved channel during the fiber laser-MIG hybrid welding process, an attenuation filter with lower transmittance was used to control the entry of light. With the lower transmittance attenuation filter, the high-speed video images of plasma induced during laser-MIG hybrid welding are shown in Fig. 4. The acquiring frequency of the high-speed camera is also 1000 frames s^{-1}.

The images show that the curved channel is composed of two parts: A and B. A is formed near the position of the impinging laser beam. It is generated from the laser-induced plasma; however, it is increasing in brightness and size. B is formed near the welding wire tip. It comes from the core of the electrical arc induced during MIG; however, its direction changes.

3.2 Spectra of plasmas

Fig. 5 shows the spectra of plasmas induced during laser-only welding, MIG-only welding, and laser-MIG hybrid welding. The spectrum of plasma induced during laser-only welding is very weak compared with those of the other two kinds of plasmas. There is a very pronounced peak visible around the wavelength of fiber laser (1070 nm) during laser-only welding. This 1070 nm line spectrum is formed by the scatter laser beam. In MIG-only welding, the 1070 nm line spectrum is not observed because of the absence of the laser beam. In laser-MIG hybrid welding, the 1070 nm line spectrum is again observed due to the coupling of the laser beam and its intensity is weaker than in laser-only welding. This indicates that the less-scattered laser beam can be detected in laser-MIG hybrid welding than in laser-only welding because the laser beam is shielded partially by the arc plasma in laser-MIG hybrid welding.

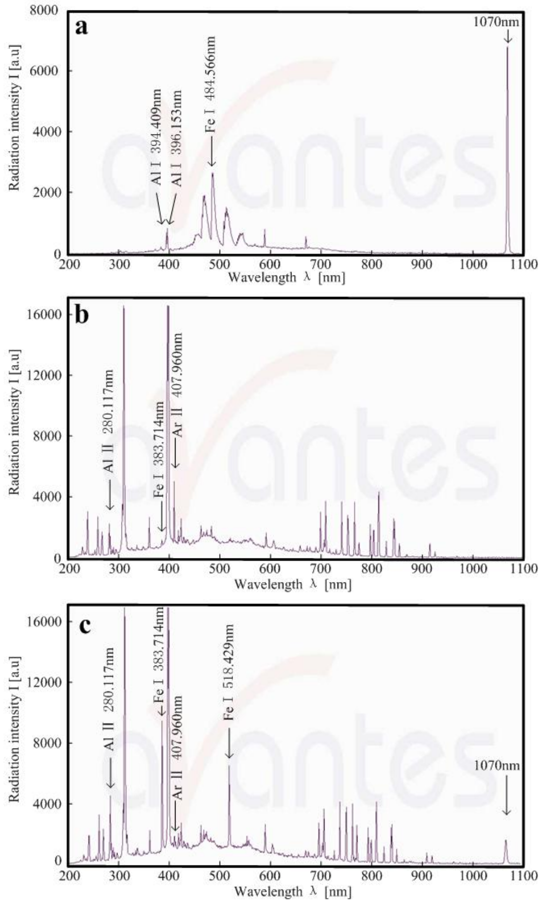

Fig. 5. Spectra of plasma (a) laser; (b) MIG; (c) laser-MIG hybrid welding.

The continuous spectrum from 400 to 600 nm is dominant in laser-only welding. Only a few line spectra of neutral atoms can be found, such as Al and Fe. The ion spectra of alloying elements and the line spectra of an argon neutral atom are not detected. The above spectroscopic images demonstrate that the plume induced in laser-only welding consists of metal vapor from ZL114 alloying elements; however, this is not necessarily evident in the ionized state.

The line spectra of the laser-MIG hybrid welding plasma

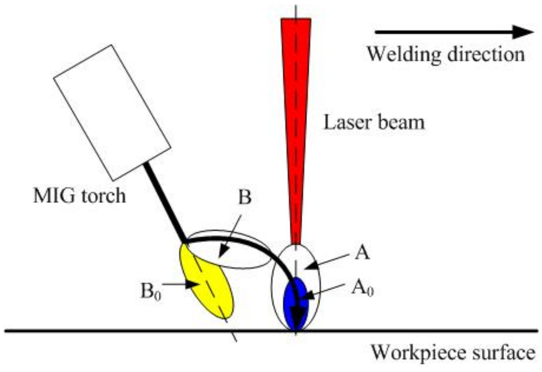

Fig. 6. Schematic of the two regions of hybrid plasma.

are basically the same as those of the MIG-only welding plasma. However, the radiation is more intense than in MIG-only welding. The arc plasmas of both MIG-only welding and laser-MIG hybrid welding mainly consist of Al, Fe, and Ar emission lines. However, the spectral intensities of Al and Fe in laser-MIG hybrid welding are much stronger than those in MIG-only welding [e.g., Al Ⅱ (280.117 nm) and Fe Ⅰ (383.714 nm)]. At the same time, the spectral intensities of Ar in laser-MIG hybrid welding are much weaker than those in MIG-only welding [e.g., Ar Ⅱ (407.960 nm)]. These indicate that the arc plasma composition changes. In addition, more vapor lines are detected in laser-MIG hybrid welding than in MIG-only welding [e.g., Fe Ⅰ (518.429 nm)].

4. Discussion

The experimental results demonstrating the schematic of the hybrid plasma are shown in Fig. 6.

Here, A_0 is the plasma induced during laser-only welding, which is directed vertically to the workpiece, whereas B_0 is the core of the electrical arc during MIG-only welding, which is directed along the wire axis. The curved arrow represents the direction of the hybrid plasma from the welding wire to the workpiece during laser-MIG hybrid welding. The hybrid plasma can be divided into two zones: Region A and Region B.

Region A

Region A is generated by Region A_0 (i.e., the laser-induced plasma). The most significant change is that its size increases, representing the increase in ionization and temperature in Region A.

In MIG-only welding, the arc plasma is maintained by thermionic emission from the workpiece. Because the maximum temperature of the welding pool is far below the evaporation temperature of the workpiece, the argon gas is mainly ionized to conduct an arc current. Therefore, the arc plasma of MIG-only welding mainly consists of the element Ar and only a very small part of the metal element. In contrast, during laser-MIG hybrid welding, a keyhole is formed in the welding pool by laser radiation, and laser-induced metal plasma/vapor is ejected from the keyhole opening. The metal plasma/vapor comes into the arc plasma, which changes the arc composition, especially in Region A. Because the ionization energy of Al and Ar atoms is 5.96 and 15.76 eV, respectively, the metal atoms have a much lower ionization potential, and are therefore more easily ionized than the atoms of the argon gas. The laser-induced metal plasma/vapor becomes ionized and replaces some of the ions of the argon gas. Thus, the spectral intensities of metal elements in the laser-MIG hybrid welding are much stronger than those in MIG-only welding, whereas the spectral intensities of the Ar element are much weaker. A large number of metal atoms are ionized to conduct the arc current, which reduces the energy required to maintain it. Moreover, the arc is rooted to the keyhole, and the high-temperature keyhole turns into the thermionic emission point; thus, thermionic emission very easily takes place. The combined effect of the laser and MIG arc leads to an increase in the size of Region A.

The mechanism of arc stabilization is based on the enhancement of the arc plasma ionization. The aforementioned phenomena lead to increased ionization and, consequently, to arc stabilization.

The laser-MIG hybrid plasma has a stronger intensity at the surface near the welding pool because of the increase in the size and brightness of Region A, which creates more heat that acts directly on the welding pool.

Region B

Region B comes from Region B_0 (i.e., the core of the electrical arc). The most significant change is that its direction is altered.

Under normal circumstances, the arc selects the route between the electrode and the workpiece that has the smallest electrical resistance. Because Region A forms an ionization duct that provides a significant number of charged particles, it contributes to the discharge current and the electrical conductivity increases. The resistance of this duct is smaller than that of other locations. Consequently, the core of the electrical arc can be guided to the location of the laser beam through the duct and its direction is altered.

From the above, the compositional change in the plasma due to the laser-induced evaporation of the workpiece material during laser-MIG hybrid welding leads to a reduction of the effective ionization potential of the plasma, and provides a more conductive, stable plasma channel between the wire and the keyhole. In contrast, the arc is attracted to the keyhole, and the high-temperature keyhole turns into the thermionic emission point. Thus, thermionic emission takes place very easily, and the stability of arc plasma is improved. This also increases the utilization of energy. The absorption coefficient of laser increases because the impinging spot of the laser beam is on the high-temperature molten pool.

5. Conclusion

The hybrid plasma forms a curved channel between the welding wire and the keyhole during the CW fiber laser-MIG hybrid welding process. The curved channel is composed of two parts. The combined effect of the laser and MIG arc leads to an increase in the size of Region A. The laser-induced plasma/vapor expands and forms an ionization duct that is one part of the curved channel. The core of the electrical arc is guided to the material through the duct, which is the other part of the curved channel.

The arc plasmas of both MIG-only welding and laser-MIG hybrid welding mainly consist of emission lines of the metal element and shielding gas element. However, the spectral intensities of the metal element in laser-MIG hybrid welding are much stronger than those in MIG-only welding, whereas the spectral intensities of the shielding gas element in laser-MIG hybrid welding are much weaker, especially in Region A.

The molten pool is generated in the position irradiated with the laser beam, and the high-temperature keyhole turns into the thermionic emission point. Thus, the arc is rooted to the keyhole. The laser-MIG hybrid plasma has a stronger intensity at the surface near the welding pool, creating more heat, which acts directly on the welding pool.

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