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Technical Paper

# Effect of distance between the heat sources on the molten pool stability and burn-through during the pulse laser-GTA hybrid welding process

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ABSTRACT

To solve the burn-through defects during the thin plate welding process, in this paper, by utilizing the characteristics of flexible regulation of the pulse laser, the pulse laser arc welding hybrid welding process was used to perform the butt welding experiments on the thin plate of titanium alloy. The weld morphological characteristics were observed and analyzed. The dynamic behaviors of the molten pool and keyhole were monitored by high speed camera. Additionally, the coupling arc plasma characteristics were acquired by spectrograph. The results showed that the welding parameter the distance between the axis of laser beam and the tip of the GTA electrode (DLA) seriously affected the stability of the welding process. By adjusting the DLA precisely, the keyhole and molten pool behaviors could be controlled and the satisfactory weld formation was obtained. In addition, the weld burn-through defects could be divided into two kinds. When the coupling state was better, which possessed a more concentrated energy and larger arc force, it was easy to cause the continuous burn-through weld. While when DLA was commensurate with the length of the arc, the “keyhole” was located in the end of the arc and was heated continuously by the arc, resulting in local burn-through defects.

## 1. Introduction

In order to adapt to the development concept of efficient production, automatic welding technology, which possesses characteristic of high efficient, fixed parameters and convenient operation, has been widely used in various processing and manufacturing fields [1]. However, during the thin plate of automatic welding process, the welding process of the thin plate is sensitive to welding parameters, and the flexibility of parameter adjustment is poor, thus the burn-through still occurs [2]. Therefore, improving the stability of welding and suppressing burn-through occurrence are great significance to the development of efficient thin plate welding technology. Researches indicated that the molten pool behaviors at the bottom weld pool (mainly affected by the combination of arc pressure, gravitational force, and surface tension), had significant influence on suppressing burn-through, only when these forces coordinated with each other and achieved balances, it could keep the molten pool stable [3,4]. In addition, burn-through occurred when the sum of arc pressure and gravitational force on the bottom of molten pool was greater than the surface tension [5]. From the theory analysis, it could be found that in order to ensure the molten pool stability and obtain a properly penetrated weld during thin plate welding, it is an effective means to heat the molten pool intermittently, reduce the heat input and the molten pool size, and increase the surface tension at the bottom of the molten pool. For improving the stability of the molten pool during welding of thin plates, a lot of works had been carried out. In order to suppress the burn-through in thin plate welding process, pulse arc and CMT welding, which achieved intermittent heating of the molten pool, was commonly used in melting welding process [6,7] to obtain good welding formation, but the low welding speed restricted the further development of the technology. Thus, it was of great importance to seek a thin plate welding process with the characters of efficient, easy-to-operate, well controlled, and this should be accomplished based on fusion welding.

The pulse laser-GTA hybrid welding process, consisting of a high penetrability pulse laser and a good gap tolerance arc, has attracted considerable attentions recently for its particular advantages in comparison with single arc or laser welding, such as greater joint fit-up tolerance, improved gap tolerance, and more adjustable parameters [8–10]. Because of the addition of pulse laser, this kind of hybrid welding shows obvious advantages in regulation of heat source states to adapt to different welding needs [11,12]. Nevertheless, for the burn-through defects in hybrid welding process, their approach is mainly to

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increase the welding speed or reduce the heat input, which will narrow the selected range of welding parameters [13–15]. Meanwhile, it is noted that the additional laser has a strong regulation effect on the arc, if the laser parameters arc changed, different molten pool flow conditions and surface tension of the molten pool can be obtained [16,17]. In addition, according to the reports, it can be seen that the distance between the axis of laser beam and the tip of the GTA electrode, defined as DLA, is an important parameter that plays a decisive role in controlling the welding state during the welding process [18–20]. Under the condition that the output energy of the heat sources remains unchanged, adjusting the DLA can obtain the different heat source states. Thus, it can be found that by controlling the heat source status with the parameter DLA, it is possible to effectively improve the stability of the molten pool.

In this research we performed a comparative experimental study on the mechanisms in the pulse laser-GTA hybrid welding process using different DLA. By investigating the welding phenomenon such as weld joint appearance, induction efficiency, arc plasma characteristics and weld pool behaviors, some models were established to help understand the inner processes during welding, and at last, differences in the inner interactions between laser and arcs were analyzed detailedly. It is thought that this study will give help researchers in laser-GTA hybrid welding area.

## 2. Experimental procedures

The welding system consisted of a pulse Nd: YAG laser beam and a paraxial arc generated by a GTA welder, as schematically shown in Fig. 1(a). The laser with the wavelength of 1.064 μm was focused by a lens with a focal distance of 120 mm into a spot measuring about 0.6 mm on the surface of the workpiece. The average output power of the laser could be adjusted from 0 to 1000 W by controlling the pulse energy, pulse duration and pulse frequency. In the hybrid welding process, the arc operated continuously while the laser operated in the form of pulse, and the laser irradiated vertically to the workpiece, while the angle of the arc torch axis to workpiece surface was kept 45°. Argon with purity of 99.99% was utilized as the shielding gas, and the flowrate is 10 L/min. The vertical distance between the tip of the electrode and workpiece was 1.5 mm. And the experiments were performed at welding direction of arc leading. In addition, titanium alloy was identified as a highly reactive material at ambient gases, especially at high temperature (above 300 °C), thus, during welding process a trailing shielding gas with the flowrate 20 L/min was used to protect the molten pool from oxidation. In addition, an improved "sandwich" test method was used to observe the dynamic behavior of the keyhole during the welding process, as shown in Fig. 1(b).

In order to further study the hybrid plasma characteristics, plasma spectrum at acquiring position in vertical plane was acquired and analyzed, as shown in Fig. 2. The SP-2556 spectrograph with 500 mm focus was used to acquire the plasma spectra. As shown in Fig. 1, the light emitted from the arc plasma was imaged 2:1 by a convex quartz lens in order to improve the location accuracy of acquiring system. The fiber head was fixed to an X-Y controlled device, which ensured the accuracy of 0.01 mm. A computer was used to control the spectrograph and manage the information acquired. Plasma emissions passing through the grating were detected by charge coupled device at the working temperature of 203 K. In this paper, 300 groves/mm grating with a spectral resolution of 0.128 nm was used to acquire the spectrum of the welding plasma, as shown in Fig. 2, then the spectrum of the hybrid welding arc plasma with the wavelength from 200 to 1000 nm was acquired. It also could be seen that the arc plasma was mainly composed of Ti atoms, Ar atoms, $Ti^+$ ions and $Ar^+$ ions. According to the line selected principle of relative intensity method, in this research, the electron temperature $T_e$ of the coupling arc plasma was calculated by lines of Ti I 439.39 nm and Ti I 453.49 nm. A data cable transmits spectra data to the software in a computer that can process and display the data acquired. In this work, the exposure time was set to be 1.0 ms and the readout time was about 13.4 ms. The acquiring position is located at the intersection of the laser incident path and the axis of the electrode.

Besides, a diode laser with a central wavelength of 808 nm and adjustable output power of 0–30 W was employed as the assistant illumination source. The light beam was focused into an elliptic spot that was large enough to cover the entire molten pool surface. The maximum power density of elliptic spot was about 9.55 W/cm$^2$. A high-speed camera was positioned towards the laser action point to acquire the details in this area including the keyhole formation and annihilation, molten pool surface and arc plasma behavior. The acquiring frequency of the camera was set to be 2000 frame/s. Data collected was transmitted to corresponding software by a cable and was shown as visible images. A narrow band filter with a central wavelength of 809.5 nm and a passband half width of 9.2 nm was placed in front of the high-speed camera. In whole experiment, the workpiece moved along the direction and the hybrid welding torch fixed, so the entire welding process could be monitored in real time.

Because the pulse laser could lead to a periodic change of GTA arc and molten pool, the each laser cycle of welding process could be divided into two alternate sections: during laser action and after laser action. In this study, the high speed camera owned a high resolution time (0.5 ms) and the laser pulse duration (3 ms), which was much greater than 0.5 ms, so it could distinguish each picture that was captured during laser action or after laser action. However, for the spectrograph, its resolution time (10 ms) was low, which was greater than 3 ms, so every measurement period included both during the laser action period and after the laser action period. In this way, the captured information was identified as during laser action in later descriptions for simplification.

Since liquid titanium alloys that was melted in welding process possessed low surface tension, good liquidity, and easy to burn-through, it was difficult to maintain the stability of the molten pool, meanwhile,

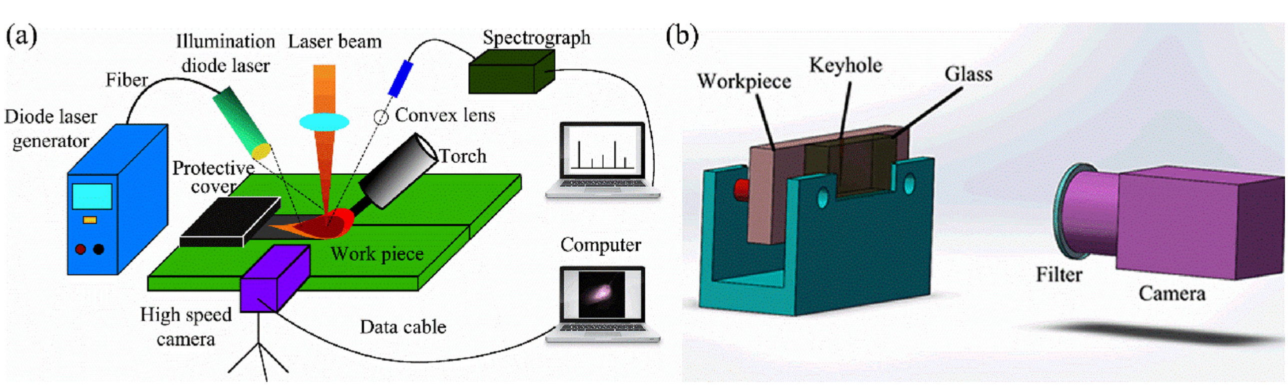


**Fig. 1.** Schematic diagram of welding process.