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Experimental and theoretical characterization of deep penetration welding threshold induced by 1-μm laser

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ABSTRACT

The deep penetration-welding threshold (DPWT) is the critical value that describes the welding mode transition from the thermal conduction to the deep penetration. The objective of this research is to clarify the DPWT induced by the lasers with wavelength of 1 μm (1-μm laser), based on experimental observation and theoretical analysis. The experimental results indicated that the DPWT was the ratio between laser power and laser spot diameter (P/d) rather than laser power density (P/S). The evaporation threshold was smaller than the DPWT, while the jump threshold of the evaporated mass flux in the molten pool surface was consistent with the DPWT. Based on the force balance between the evaporation recoil pressure and the surface tension pressure at the gas–liquid interface of the molten pool as well as the temperature field, we developed a self-focusing model, which further confirmed the experimental results.

1. Introduction

In laser welding, there are two types of welding modes: thermal conduction mode (shallow penetration-type) and deep penetration mode (keyhole-type) [1,2]. The latter one leads to a deep penetration weld with high aspect ratio and it is the high efficiency of laser welding. A deeper understanding of the welding mode transition from the thermal conduction mode to the deep penetration mode is thus essential to comprehensive understanding the laser welding process.

The deep penetration welding threshold (DPWT) is the critical value to characterize the laser welding mode transition, and it should be independent of the laser spot size. At present, the DPWT definition differs in two ways: power density (P/S) [3–8] and the ratio between laser power and laser spot diameter (P/d) [9–12]. Where P is the laser power, S is the laser spot area, and the d is the laser spot diameter. The former one of which is most common in the current literatures, but some studies [9,12] have showed that the P/d is more suitable than the P/S for characterizing the DPWT. However, the P/d was obtained under the following condition: the DPWT was equal to the evaporation threshold. Hirano et al. [13] pointed out that the molten pool surface stayed almost flat when the surface center temperature was equal to the evaporation temperature, indicating that the welding mode was still the thermal conduction mode and the evaporation threshold was obviously smaller than the DPWT. Thus, the DPWT characterization still needs to be further clarified in details.

As 1-μm laser welding has been receiving wide attentions owing to their advantage such as the better flexibility in terms of the fiber transmission. In this research, we selected the Nd:YAG laser that is a typical type of 1-μm laser. The characterization of DPWT was deduced by experimental observation and theoretical analysis. When the welding mode suddenly changes, the principal reason is the jump of laser energy absorption. Thus, the self-focusing effect is taken into account in the theoretical analysis.

2. Materials and experimental procedures

The CW Nd:YAG laser (CW025, Rofin company, Germany) used here features a wavelength of 1064 nm and a maximum power of 2.5 kW. The laser beam was delivered through the optical fiber of 0.6 mm in core diameter, focused into 0.36 mm in spot diameter by the lens of 120 mm focal distance. The shape of plume was observed with a color high-speed camera (Fastcam 1024R2, PHOTRON Co. Ltd., Japan) at the frame rate of 2000 frames s^{-1}. The six-axis linkage machine tool (Arnold Company, Germany) was adopted for the operation system. The molten pool was protected by using argon in the paraxial nozzle with 3 mm in inner diameter. The angle of the nozzle axis to the laser beam axis was 45°. The shielding gas flow

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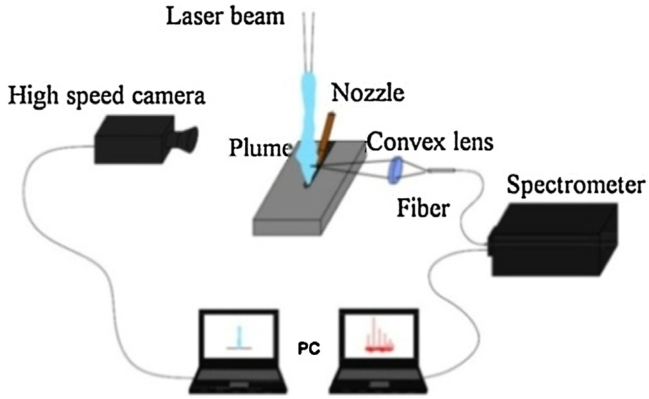

Fig. 1. Schematic diagram of the experiment setup.

direction was consistent with the direction of welding. Schematic diagram of the experiment setup is presented in Fig. 1.

The spectra were recorded by using a spectrometer (SP-2500i, Acton Company, America). A thermoelectrically cooled CCD, manufactured by Princeton Instrument, was used as a detector with the working temperature of −20 °C. The radiation from the plume was projected by a convex lens of 120 mm focal distance onto an image plane with a magnification of 2:1. An optical fiber tip fixed on a table was aimed toward the plume at the image plane. The detecting position of spectrometer was at the center of laser beam, 0.5 mm height above the sample plate surface. Then the signals were coupled through an optical fiber to the spectrometer, transmitted to the computer and displayed with the WinSpec/32 software. A 300 g mm^{-1} grating was used. The integration time for the spectroscopic measurement was 20 ms.

The welded material was A3 steel with a size of 100 mm × 50 mm × 10 mm. The chemical composition of A3 steel used is Fe–0.12C–0.4Mn–0.3Si–0.05 S–0.05P, wt.%. Before welding, the surface of welded material was polished. And the residue in material surface was removed by applying acetone. The laser power and focused spot were measured by using beam quality diagnosis instrument (Prometec UFF100, Germany) before welding. The bead-on-plate welding was carried in welding speed of 1 m/min. The defocus distance were 0 mm and 1.5 mm during welding, and the corresponding spot diameter at the sample surface was 0.36 mm and 0.55 mm, respectively. The shielding gas flow of 15 L min^{-1} He was used. For each weld parameters, the welding process was repeated three times. Six cross-sections were obtained at the middle part of the weld seam from each weld sample. The distance between each cross-section is about 5 mm. After the grinding, polishing, and etching, the weld depth of each of these six cross-sections was measured by using an Olympus optical microscope.

3. Experimental results

Fig. 2 shows the plume behavior and welded seam cross-section under different laser powers. The increase of weld penetration was not linearly correlated with the increase of laser power from 0.32 kW to 0.52 kW. The weld penetration was almost same when the power was below 0.44 kW. The penetration jump was observed at the power of 0.48 kW, indicating the laser power of the welding mode transition was between 0.44 kW and 0.48 kW. When the laser power was 0.32 kW, the yellow red plume had been produced above molten pool surface. An obvious plume above the molten pool surface was observed when the laser power increased. Therefore, the evaporation threshold of as-welded A3 steel was smaller than the DPWT.

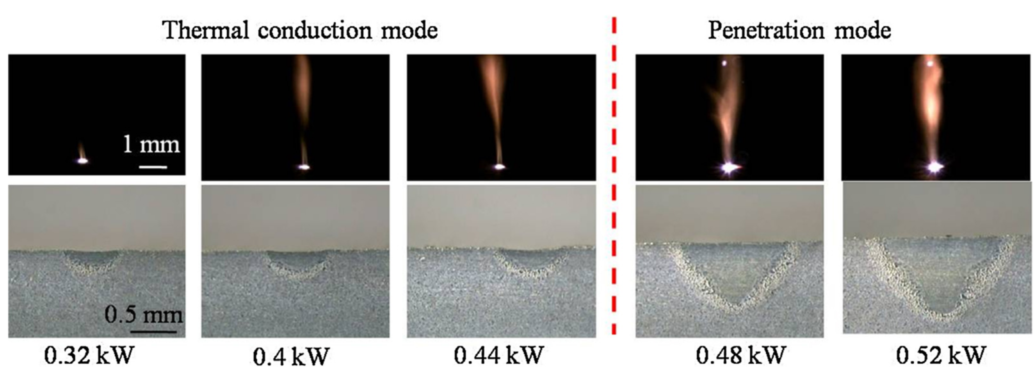

Fig. 2. Plumes and cross-sections of welds at different laser powers (v = 1 m/min, d = 0.36 mm).

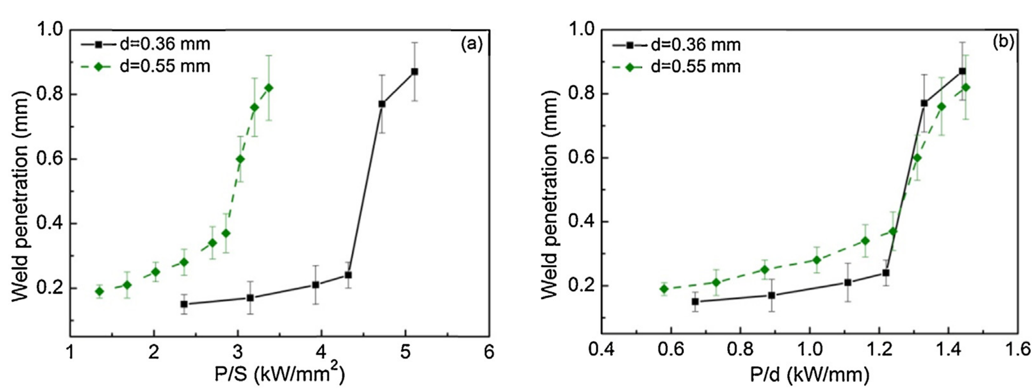

Fig. 3. Relationship between weld penetration and P/S or P/d (v = 1 m/min). (a) P/S, (b) P/d.