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Experiment study and regression analysis of molten pool in laser welding

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ABSTRACT

Relationship between welding parameters and molten pool morphology was investigated by experiment analysis. The welding experiments were designed by Taguchi L27 method, while laser power, welding speed and defocusing distance were considered. The periodical change of molten pool had been observed. Defining and extracting the length of the molten pool, the width of the molten pool, the area of the molten pool in one period. The oscillation period of the molten pool also can be obtained. The influence of laser power on molten pool morphology was greater than that of welding speed and defocusing distance. Welding speed play a negative effect on molten pool morphology and oscillation period. Defocusing distance had a complicated effect on molten pool morphology and little effect on oscillation period. Applying statistical analysis, four nonlinear regression equations were established between process parameters and molten pool morphology. Mean relative errors were less than 5%, which mean the predicted value of the regression equations matched well with the actual value.

1. Introduction

Laser welding owing to its advantage in narrowly focusing laser beam, small heat-affected zones and high efficiency processing, has been increasingly adopted in various industries [1–3]. Dynamic behavior of molten pool can cause the variation of welding quality such as the external defects in the weld and mechanical properties of the parts [4,5]. Numerous researchers have explored effective detection methods to study the change rule of molten pool in welding process. The molten pool movements may be explained by the integrated of 4 forces: (1) forces of the vapor pressure of liquid metal, (2) the fluid gravity in the keyhole, (3) the blowing force of shielding gas, (4) the drag force. The molten pool shape was affected by the process parameters which altered the forces. The shape and the depth of molten pool was of greatest importance to the thickness and the strength of the weld. Experiments have been completed to illustrate the influence of process parameters on molten pool [6,7]. As a result of the morphology of molten pool was complicated and variable, it was difficult to directly measure the molten pool's dynamic changes [8]. Machine-vision sensing methods provided direct information on molten pool surface and high-speed camera captured the top geometry of the molten pool [9,10].

Many visual methods were used to research molten pool, but the quantitative analysis of molten pool was relatively rare. Gao et al. [11] applied a coaxial visual sensing system in Nd: YAG laser welding of stainless steel to record the images of molten pool and keyhole, furthermore, based on the gray character of molten pool and keyhole in images, an image processing algorithm was designed to get the welding quality information. Anh NV [12] adopted the measurement of the 3D convection inside the molten pool in PKAW by stereo synchronous imaging of tungsten tracer particles using two sets of X-ray transmission systems. The 2D convection on the molten pool surface was also measured using zirconia tracer particles, but the molten pool morphology was not obtained. Kim et al. [2] devised a visual sensing system to observe the morphology of keyhole and molten pool in a laser remote welding. Luo et al. [13] extracted the welding pool edge and characterized the width of weld seam. Yamada et al. [8] used X-ray image of inside materials with intense synchrotron radiation to observe molten pool and defects during laser welding, and the relation between molten pool shape and welding quality were studied, but the cost of the equipment was a burden. Li et al. [14] carried out an experiment on high-power laser welding of thick plate finding that with the increase of welding speed, the width and depth of weld seam decreased. The flow pattern of molten pool was observed to be instable and changeable under different welding

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parameters, but the quantitative relationship was not established [15]. And the results might be improved if some special processing measures can be taken [16], but there need more experiment and research to verify them. Some researchers even employed numerical simulation methods according to the theory of conversation of energy to acquire the shape of the molten pool, and assess welds quality [17–19], but it was not an easy path. Moreover, most researchers didn't tell how to choose molten pool image in thousands of captured images. The reason why the chosen image was the most representative wasn't clarified clearly. The targeted experiments were still required.

In this paper, the periodic variation in the growth and shrink of molten pool was observed and analyzed. The procedures of selecting the images who represented the molten pool morphology were introduced in detail. The molten pool information was extracted from the selected image. The influence of processing parameters on the morphology of molten pool was deeply discussed. The regression relationship between multi-process welding parameters and molten pool morphology was established.

2. Experiment setup

The welding material was stainless steel 316L with size of 100 × 100 × 10 mm. The experimental system consisted of an IPG YLR-4000 fiber laser welding device (focal distance 250 mm, beam diameter 0.3 mm), an ABB IRB-4400 6-axis robot, a high-speed camera (Fps: 5000), a diode laser auxiliary light source and a camera with a narrow-band filter. The light source was adopted to illuminate the molten pool whose vision information can only be received by the camera. The camera can eliminate the radiation interference of molten pool, plasma, spatters and laser beam. Laser beam incident angle between central line of laser head and the vertical line on the surface of the part was 15 °. The shielding gas wasn't adopted in order to reduce the influence of external environment on molten pool morphology (see Fig. 1).

The multi-process parameters were laser power, welding speed and defocusing distance (D), each parameter had 3 values. A three-factors and three-levels experiment method using Taguchi L-27 orthogonal array was designed in Table 1.

3. Methodology

3.1. Definition of molten pool morphology

The captured molten pool images were presented in Table 2. The molten pool morphology parameters mainly included the length of the molten pool (LMP), the width of the molten pool (WMP), the area of the molten pool (AMP). LMP was the longest

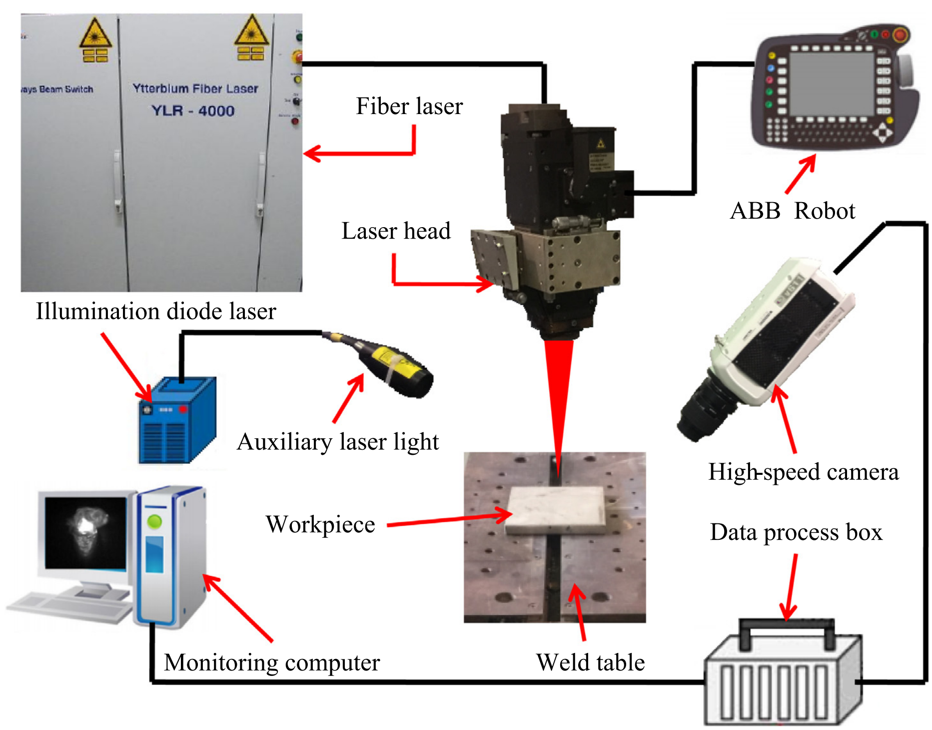

Fig. 1. Schematic diagram of fiber laser welding experiment setup.

Table 1
Welding parameters adopted in the experiment.

NO.	P (kW)	S (mm/s)	D (mm)	NO.	P (kW)	S (mm/s)	D (mm)	NO.	P (kW)	S (mm/s)	D (mm)
1	2	20	−2	10	3	20	−2	19	4	20	−2
2	2	20	0	11	3	20	0	20	4	20	0
3	2	20	+2	12	3	20	+2	21	4	20	+2
4	2	30	−2	13	3	30	−2	22	4	30	−2
5	2	30	0	14	3	30	0	23	4	30	0
6	2	30	+2	15	3	30	+2	24	4	30	+2
7	2	40	−2	16	3	40	−2	25	4	40	−2
8	2	40	0	17	3	40	0	26	4	40	0
9	2	40	+2	18	3	40	+2	27	4	40	+2