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Dynamic features of plasma plume and molten pool in laser lap welding based on image monitoring and processing techniques

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HIGHLIGHTS

- Plasma and molten pool instantaneous images in different gap were observed.
- The dynamic features of plasma and melt pool were extracted.
- The time domain and frequency field of plume and molten pool were calculated.
- A novel monitoring method for gap was obtained.

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ABSTRACT

Laser lap welding is the typical welding mode for laser-welded steel sandwich constructions, and the welding quality is a critical point for their comprehensive performance. However, the special welding mode for the sandwich plate proposes challenges attributed to the gap between upper plate and below plate are difficult to be avoided and so real-time monitoring of gap is very important in laser welding. On the basis of the plume and molten pool images captured by two high-speed cameras, the characteristics of instantaneous plasma plume and molten pool were calculated, and their process parameters were extracted statistically in time domain and frequency field. After preprocessing the images, the quantification of the plume and molten pool was performed. Using static and dynamic features of plume and molten pool, the effect of gap on the welding procedure was discussed for laser lap welding. The results revealed that the gap was closely related to the dynamic variation of plasma plume and molten pool. The dynamic features of plume and molten pool could be better reflected by the plume area, peak frequency and molten pool length in different gap. The monitoring method based on the synthetic characteristics of vapor plume and molten pool was convenient, effective and promising in production.

1. Introduction

Steel sandwich plates are lightweight structures with many advantages, including space saving and safety improvement [1]. They have great potential in ships, building, and bridge structures, especially for hazard reduction in situation of high wind, storm surge, earthquakes, and accidental blast [2,3]. Normally, the connection between the face plates and the core plates was achieved by laser lap welding, and the lap joint is the basic unit of steel sandwich structure such as V-Core and I-Core sandwich plate. However, the quality of welding joint could not be guaranteed when the gap between face plate and core plate appeared because of assembling errors and welding deformation [4]. Romanoff et al. [5] has found the global bifurcation buckling strength of laser-welded sandwich plates was significantly reduced with increasing gap. Accordingly, it is necessary to investigate plasma and molten pool behavior of laser welding for lap joints, which is helpful to develop an effective and accessible approach to monitor the gap status and welding quality during laser welding process.

Behavior of plasma plume and molten pool is closely related to the keyhole stability in laser welding, and it is significant to directly observe and measure the morphology of plasma and molten pool. Dynamic of metal vapor/plasma and molten pool could be detected by acoustical signal, optical signal, spectral signal, and electrical signals. However, the high-speed photography showed great advantages because it is able to get the spatial information and time information of the object being observed at the same time. Colombo et al. [6] proved a solution for the on-line monitoring of the gap in remote fiber laser welding of overlapped zinc-coated steel based on the analysis of the

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visible optical emission that the welding process generated, and evaluated the ability of monitoring methods to identify the effects of the variation of the gap. Gao et al. [7] obtained the molten pool morphology information by designing an active vision system. The relationship between the morphology of molten pool and the stability of the laser welding process was characterized in quantitative way, and the real-time monitoring of high power laser welding was realized with the molten pool behavior. You et al. [8] proposed an effective method for monitoring metal vapor/plume and spatters for the high-power laser welding by combining a high-speed camera with an ultraviolet and visible band-pass filter. Some intuitive information for laser welding process can be obtained by observing the plasma and the pool, But direct observation images can not precisely illustrate the processing characteristics and fluctuation mechanism of plasma plume and molten pool, which impedes further analysis.

During laser lap welding, the interference of gap on keyhole would lead to the variation of plasma and molten pool dynamic. Hence, the stability of welding process and the quality of welding seam are significantly affected by the gap [9]. Accordingly, plasma plume carried information of keyhole, which could be used to monitor the welding process. Among these monitoring methods or systems, it is of essence to design and optimize the feature information of plume/metal vapor and molten pool aiming at the concerned states. Traditional methods to assess the welding quality and stability are usually focused on the direct observations of the images and signals captured in the welding process, and the characteristic parameters of the images and signals are less investigated. However, the characteristics of the processed image and signal are more a reflection of the welding information comprehensively [10]. Therefore, when it is required to stability control during laser welding for lap joints, it would be necessary to quantitatively analyze the plasma and molten pool behavior in order to control the welding process.

In this paper, the gap was detected based on the metallic vapor/plume and molten pool for CO_2 laser welding of lap joints by image monitoring and processing techniques. In these experiments, two high-speed cameras and auxiliary laser was applied to capture instantaneous images of the metal vapor plume and molten pool during laser welding. Several main image parameters, namely, the height, inclination angle and area of vapor plume and the length, width and area of molten pool, were extracted through digital imaging technology using LabVIEW software, and the experimental data was processed using Origin software. In this way, experiment results indicated that the gap status could be evaluated and distinguished by the index effectively, and real-time monitoring and quantitative prediction of gap in laser lap welding joint were realized.

2. Experimental procedures

Fig. 1 shows a schematic diagram of the experimental layout employed during these experiments, and 4 mm thickness high-strength low alloy (HSLA) steel was used as a specimen in this experiment. All samples of the steel plate contain 0.16% C, 0.22% Si, 0.58% Mn, 0.019% S and 0.013% P except Fe. A high power CO_2 industrial laser (Trumpf, TLF 15000) capable of up to 15,000 W in CW mode was operated with −2 defocusing amount on the samples, and the M2 value of the laser beam was about 3.6 and the spot diameter was 0.86 mm. A plate welding with the speed of 1.5 m/min was carried out under the constant laser power of 8 kW.

The upper plate and below plate were assembled by a clamping device and joined by tack welding after setting gap, which guaranteed that the gap gradually increased from 0 to 1 mm, with the interval of 0.2 mm using feeler gauge. All samples were cleaned by acetone manually before welding. The working head was stationary during the welding process, and the platform on which the workpiece was fixed moved at a constant speed along the length direction of the specimen. Pure Helium shielding gas was blown forward through a nozzle of a 6 mm internal diameter at a flow rate of 30 L/min. The gas nozzle was located in the leading direction.

During laser lap welding, two high-speed cameras were used to take the images of metal/vapor plasma and molten pool above the workpiece top surface. The flaming rate of the video was set as 1000 frames per second for the plume and 750 frames per second for molten pool. Laser induced plume and molten pool were observed by high speed camera placed in the horizontal plane and in the 65° dip angle, respectively. The molten pool was illuminated with a diode laser from horizontal plane with a 30° dip angle.

High speed camera system (HSCS) included high speed camera, Marco lens, dimmer glass, interference filter and UV Lens (see Fig. 2). Camera that produced in Switzerland was MV-D1024-TrackCam of Photon Focus Company (Max10000 fps), and the least exposure time was 0.01 ms. The optical zoom range of CMOS camera was 18–45 mm. The images were transmitted from the camera to a computer through a digital cable at a specific moment during the welding process. Plasma plume image could be easily acquired using a high-speed camera equipped with an attenuation lens. Molten pool image could not be observed due to its interference of plasma light and dynamic variation. In this study, a high-speed camera equipped with an 808 nm narrow band pass filter and two attenuation lens was utilized to record the morphology of molten pool. A 2 W diode laser at a wavelength 808 nm was employed to illuminate the surface of molten pool and form its region of Interest (ROI). A narrow band filter was used to eliminate the optical interference of spatters, welding laser beam and plume, and allowed the camera only to receive the radiation of diode laser illuminant.

3. Results and discussion

3.1. Imaging processing

The instantaneous metal vapor/plume and plasma images acquired by high-speed camera were observed in laser lap welding. Fig. 3 shows the continuous flaming images of metal vapor/plume in different gap size. It could be seen that the size and shape of the plume showed little change when gap was zero, and the tilt angle of plume was mostly perpendicular to specimen surface. However, the upper plasma plume presented obvious period fluctuation with increasing time when gap was 0.6 mm, and the tilt angle of plume become smaller. The tilt direction of the plume was opposite to the welding direction. The upper plasma become less with metal vapor/plasma erupting from the gap, and that leaded to the dynamic change of plasma plume at the large gap.

Typical images of plasma plume were taken from different gap for comparison, as shown in Fig. 4. The height and shape of plasma plume was little difference when the gap was less than 0.4 mm, and plasma was also not observed at the gap. However, the size and tilt angle of plasma plume become smaller together with the plume appeared at the gap. Plasma plume escaped from the gap due to front keyhole wall was broken at the gap, and the upward eruptible plume weakened. Front keyhole wall could not maintain with 1 mm gap, and plume continuously erupted from keyhole at the gap. For convenience of description, the metallic vapor was divided into upward plume and middle plume since metallic vapor/plume could get away from keyhole opening at the top and the keyhole front wall at the gap. During laser lap welding, the effect of the gap on keyhole and its walls could be observed through metallic vapor escaping from the upper keyhole opening. Although the flow of vapor into the surroundings was mainly determined by the conditions at the opening of the keyhole, there were other outlets at the front wall of the keyhole at large gap under some circumstances.

Fig. 5 represents the continuous change of keyhole opening and the molten pool in CO_2 laser welding in different gap sizes. As shown in Fig. 5, the size and shape of keyhole opening periodically fluctuated