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Correlation analysis of penetration based on keyhole and plasma plume in laser welding

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ABSTRACT

The variation characteristics of the keyhole and the plasma plume are monitored by using high speed camera. The time and frequency domain characteristics of keyhole area (KA) and centroid high plasma plume (CHPP) are analyzed. A covariance mapping technique is applied for the frequency correlation. The KA and the CHPP have different variation in the time domain and similar variation in the frequency domain. The dominate frequency is located in a low-frequency component (0–4000 Hz) under the different penetration modes. The mean spectrum barycenter of partial penetration mode is higher than that of the full penetration mode. There is a high positive correlation in low-frequency component. The frequency of KA between 1500 and 2600 Hz in the partial penetration mode and the frequency below 2000 Hz in the full penetration mode have a high positive correlation with that of the CHPP. The results of the study provided a basis for the on-line inspection of laser welding of tailor rolled material (TRM).

1. Introduction

Laser welding is extensively used in modern industries due to the high energy density, high production efficiency, ease of automation and minimal thermal deformation. The plasma plume and the keyhole are important physical phenomena during the equal thickness laser welding process. The variation characteristics of plasma plume and keyhole have a great influence on the stability of welding. Compared with laser welding of equal thickness, Tailor rolled material (TRM) laser welding process is more complicated. In order to get better the stability of the welding process and the quality of the weld, penetration state of the laser welding process is more need monitored.

Many penetration monitoring methods are used in industry production. According to monitoring target, monitoring methods are divided into the three categories of single-sensor single-target monitoring, multi-sensor single-target monitoring and multi-sensor multi-target monitoring. Sibillano et al. (2012) showed that the spectroscopic monitoring of penetration depth is applied to different laser sources (c.w. CO_2 laser, cw fiber laser and pulsed Nd: YAG laser). The acquired spectra of different laser sources revealed different characteristics. In this research, the electron temperature of plasma plume is used in the on-line monitoring of penetration depth. Chmelickova et al. (2013) showed that the plasma plume in the welding process is controlled by the plasma intensity measurements. Plasma control system is based on the electron temperature of plasma plume from the relative intensities of couple of emission lines. Oezmert et al. (2013) found that the change of penetration is detected by the change of weld pool contour and process emission spectrum of copper. During the full-penetration state, a 50% elongation of the weld pool contour is observed in the welding direction. In addition to single spectrum monitoring, the acoustic monitoring is used in the laser welding process. Yusof et al. (2017) discussed the Feasibility of using acoustic method in monitoring the penetration status. The sound pressure level of the acquired sound is linearly related to the penetration depth. However, as the pulse width increased, the relationship is not obvious when the pulse energy reaches certain values.

With the development of camera technology, in addition to spectrum monitoring and acoustic monitoring, high-speed camera applications are more and more widely during the laser welding process monitoring. Zhang et al. (2013) showed that an on-line coaxial monitoring system with an auxiliary illuminant is built. The size of the keyhole at the top and bottom can be monitored. Lastly, the penetration status of incompletely penetrated, moderately penetrated, and over-penetrated is detected by the penetration ratio. Under the partial penetration status, Abt et al. (2011) showed that the closed loop control by using the image feature full penetration hole (FPH) is adaptable to partial penetration welding. The closed loop control is possible to reach and maintain a stable weld process under the different welding

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conditions. However, it is not a high precision when the image resolution is low and the FPH region is small by Zhao and Qi (2016). Under the full penetration status, the FPH detection algorithm is developed based on region grow algorithm. The effects of different parameters on the quality of coaxial images are investigated. The relationship of diameter of FPH between welding speed and laser power is studied by Zhao and Qi (2016).

More and more researchers pay attention to the multi-sensor multi-target monitoring. Researchers attempt to obtain the more accurate detection during the welding process by using the multiple sensor and cameras. Brock et al. (2011) have devised a photodiode sensing system for optical 3D position sensors. A significant change of the center of the vapour plume is observed by four photodiodes with the welding state changes. You et al. (2013) established a multiple-optics sensing monitoring system based on two photodiode sensors and two visual sensors. Compared with the intensity of visible light and laser reflection, the plasma plume and the keyhole are quantified. This system provided a better understanding and accurate evaluation of the welding process. More detailed information during the welding process is obtained by multi-sensing monitoring system. Gao et al. (2016) devised a multi-sensor fusion system that can capture the dynamic behavior of keyhole and plasma plume, the visible light emission and the laser reflection. The features are used for monitoring disk laser welding based on a backpropagation (BP) neural network.

Compared with the single-sensor monitoring, for multi-sensor multi-target monitoring system, the relationship between the plasma plume and the keyhole is one of the key problems. Li et al. (2015) demonstrated that the keyhole and the plasma plume are not formed simultaneously. The plasma plume appeared after the workpiece surface has been irradiated by the laser beam for 3–4 ms, whereas the keyhole is formed after the plasma plume has appeared for 10–11 ms. The laser power density threshold of plasma produced is less than that of the keyhole produced in laser welding. Tenner et al. (2015) found a relationship between keyhole behavior and plasma plume by applied different image processing steps. During high laser powers and feed rates, the keyhole and the plasma plume are well correlated. The effect of changing laser power and feed rate on the keyhole geometry is explained by using the relationship between the keyhole behavior and the plasma plume. However, the characteristics of the plasma plume include area, density distribution and inclination. Only the inclination of the plasma plume does not reflect all the characteristics of the plasma plume.

In the present work, The TC4 titanium alloy is selected. The variation and the stability of plasma plume and keyhole are monitored by using the high-speed camera simultaneously, and then the relationship between the keyhole and the plasma plume is analyzed. The correlation of penetration is analyzed by using frequency of keyhole area (KA) and centroid high plasma plume (CHPP). During the laser welding process, the penetration modes are judged by the correlation analysis of frequency domain. The correlation analysis of penetration provided a basis for the on-line inspection of laser welding of TRM. Future work will focus on researching the penetration mode real time closed-loop control system in the laser welding of TRM.

2. Experimental methods

The laser welding experiment is conducted by using a fibre laser system (IPG Photonics; wavelength: 1.07 μm; mode: TEM_{00}; maximum output power: 4 kW) and an electric welding displacement platform as shown in Fig. 1. To research how the keyhole and the plasma plume influenced one another, the morphological characteristics of the keyhole and the plasma plume are captured by using a Photons A4 high-speed camera (frame rate: 20 kHz). During the laser welding process, the plasma plume absorbed the laser energy mainly through the inverse Bremsstrahlung, which leads to the laser energy attenuation. Uspenskiy et al. (2015) showed that the total absorption of plasma is less than 1% during the welding of titanium alloy VT-23 with a high power fiber laser. The absorption of laser has little effect on the reliability of plasma plume. Therefore, in this experiment, the absorption of laser is not considered. A semi-transparent and semi-reflective lens is used to coaxially capture of the keyhole during laser welding. However, the plasma plume above the molten pool interfered with the keyhole shooting. Therefore, an 808 nm semi-conductor laser system is used as an auxiliary light source to illuminate the keyhole. A horizontal photography method is employed to capture the morphological characteristics of the plasma plume. In addition, a 350–650 mm filter lens is placed in front of the high-speed camera's lens to eliminate interference from the laser beam. The position and the angle of the high-speed camera have a great impact on the plasma plume shooting. The plasma plume is captured from a direction perpendicular to the welding direction and the laser beam but parallel to the upper surface of the workpiece in order to obtain the better plasma plume images by Zhao et al. (2016). Compared with the declination photography method, the deviation of the images of the plasma plume can be reduced using the horizontal photography method.

During the laser welding experiment, the welding material is a TC4 titanium alloy. Under the different laser power, the partial and full penetration mode welding processes are investigated shown in Fig. 1(a). The experimental parameters are as follows: welding speed 15 mm/s; defocused distance 0 mm; laser power 800–1200 W; flow rate of the side Ar shielding gas 15 L/min. The different shielding gas is discussed in order to protect the weld zone. Reisgen et al. (2010) showed that a plasma plume consists of the ionization of both the shielding gas and the metal vapors. Hosseini Motlagh et al. (2013) analyzed the different volume ratios of He and Ar in shielding gas mixture on the power waste parameters. The argon as a shielding gas protect the work piece from oxygen during the Nd:YAG laser welding. Titanium alloy easily react with the oxygen in the air at high temperature. Therefore, the welding zone during the laser welding of titanium alloys is protected by using argon gas (Akman et al., 2009). Before the welding experiment, each weldment is subjected to a surface pre-treatment that consisted of cleaning the surface with alcohol or acetone and then polishing it with sand paper.

2.1. Image analysis

As shown in Fig. 2, the photographs of the keyhole are obtained using a high speed camera. The grey level distribution of the original keyhole image is analyzed, the fixed threshold is used to segment images of the keyhole, and the profile characteristics of the keyhole are obtained. Subsequently, the white spots from the molten pool is eliminated using an opening algorithm. Then, the profile of the keyhole is extracted, and the KA is calculated. As shown in Fig. 3, the plasma plume image is captured but contained hot pixels. Therefore, in order to obtain a clear image of the plasma plume, a median filter is used to weaken the hot pixel. There is a wide variation among the grey level of the plasma plume images at different time. Therefore, the CHPP is calculated by using the Otsu threshold and the stratification threshold method in order to analyze the effect of the density of plasma plume on the CHPP. It is found that there is little difference in the CHPP between the two methods, and the variation trend of the CHPP is similar. Although the plasma plume in the periodic is changed, there is little influence on the CHPP variation and the reliability of CHPP. Accordingly, the Otsu method is applied to analyze the plasma plume image, and then the CHPP can be calculated. In this paper, the CHPP represents the distance between the upper surface of the workpiece and the centroid of plasma plume.

2.2. Covariance mapping technique

Considering the relatively significant impact of the laser power on the KA and the CHPP, the time domain and frequency domain