Interaction between the laser beam and keyhole wall during high power fiber laser keyhole welding

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Abstract: The crucial factor of laser welding is the laser energy conversion. For a better understanding of the process, the interaction process between the laser beam and keyhole wall was investigated by observing the keyhole wall evaporation during high-power fiber laser welding. The results show that the evaporation vapor, induced by the laser beam, discretely distributed on the keyhole wall. A tiny ‘hollow’ zone was observed at the spot center-action region on the FKW. The evaporation vapor induced by the spot center moved downward along the front keyhole wall (FKW) with a period of about 0.3~0.75 ms, which indicates that the keyhole formation is reminiscent of a periodical laser drilling process on the FKW. The evaporation vapor on the keyhole wall suggest the assumption that the laser energy coupling mode in the keyhole was multiple-reflection, and the keyhole depth was mainly determined by the drilling behavior induced by the first absorption on the FKW.

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1. Introduction
With the growing demand of high-quality, high-efficiency, and high-precision welding technology for modern manufacturing in science and technology, laser welding technology attracts much attention owing to its many exceptional advantages [1,2]. In laser keyhole welding, the laser energy conversion process can be crucial [3,4]. A focused laser beam acts on a material surface, and part of the material is melted and evaporated. Then, a keyhole is formed in the molten pool due to the evaporation recoil pressure induced by the high energy density of laser beam. The laser interacts with the keyhole wall after entering it. Subsequently, the laser energy is converted to heat in the molten pool. Investigation on the interaction process between laser beam and keyhole wall is thus of great significance for understanding the laser energy conversion process in the keyhole.

Although large number of studies on laser welding have been going on for about 50 years, the mechanisms responsible for the laser energy conversion process in the keyhole are not yet fully established. For example, some theoretical studies assume that only the FKW is exposed to the incident laser beam, the FKW propagation is quasi-stationary [5,6]. Therefore, the laser energy conversion mode in the keyhole can be reminiscent of the first absorption of the FKW. Our previously shown experimental studies have confirmed that the incident laser beam directly acts on the FKW [7,8]. On the other hand, most of theoretical studies still assume that the main energy deposition mode in keyhole is multi-reflection of laser beam [9,10]. Thus, it needs a determinism about the laser energy conversion mode in the keyhole by direct observation for further understanding of the real laser welding process.

The FKW can be observed by using a high-speed camera from the top of the welded material [11,12]. The micro-morphology of the keyhole wall can be also measured by using a scanning electron microscope as the keyhole was maintained due to the rapid freezing of the melting pool [7,8]. The side morphology of the keyhole can be observed by using X-ray transmission photography [4,13,14] or the “sandwich” specimen, consists of glass and metal [1]. The time-and space resolved information about the keyhole geometry [13], melt ejections and pores formation [14] have been revealed by applying in situ X-ray photography during
laser welding. However, a few research has been done in regards to observing the interaction process between the laser beam and the keyhole wall during welding.

In this study, “sandwich” specimens, consisted of closely adhered commercial pure iron and GG17 glass, were welded by using a high-power fiber laser. The weak light in the keyhole was filtered by an attenuator, which left only the strong light of the laser-induced evaporation vapor on the keyhole wall. Through direct observation the intense laser-induced evaporation vapor, as well as the interaction process between the laser beam and keyhole wall were investigated.

2. Materials and experimental procedures

Experiments were performed by using a IPG YLS-6000 fiber laser with unpolarized state. The output power of the laser beam source was 6 kW during welding. The “sandwich” specimen was consisted of one plate of pure iron and one plate of GG17 glass. The laser was positioned perpendicular to the top surface of the specimen with a defocus amount of 0 mm. The Rayleigh length of the focused beam was 3.05 mm, the spot diameter was 0.32 mm. Three-quarters of the spot diameter was applied on the iron and a quarter of the spot diameter was applied on the GG17 glass. The molten pool was illuminated by applying a low-power laser with a wavelength of 532 nm, a power of 4 W and a diameter of 10 mm. The keyhole morphology and the metallic vapor characteristics on the keyhole wall were observed from the glass side by using a PHOTRON Fastcam 1024R2 high-speed camera. The frame rate of the high-speed camera were set to be 2000 frames per second (f/s) with a exposure time of 0.5 ms, and 8000 f/s with a exposure time of 0.125 ms. The experimental setup is shown in Fig. 1.

Fig. 1. Schematic diagram of the experimental setup.

3. Results and discussion

A typical keyhole morphology was obtained as the filter wasn't used, as shown in Fig. 2(a). The keyhole depth was approximately 10.8 mm, and the keyhole mouth width was about 0.9 mm. The inclination angle of the FKW was approximately 85°. When the weak light in the keyhole was filtered by applying a narrow-band filter (center band was 532 nm) with a transmittance of 70%, a series of obtained keyhole morphologies are shown in Fig. 2(b). These white zones discretely distributed on the keyhole wall. The FKW was slightly sloped toward the welding direction at the bottom of the biggest white zone, and manifested as a tiny ‘hollow’ zone. When the white light intensity is higher than the optical transmission threshold
of the narrow-band filter, part of the white light can be transmitted through the filter. Therefore, the phenomenon indicates that these white zones on the keyhole wall were of very high light intensity.

Fig. 2. Morphology of keyhole (2000 f/s, \(v = 2\) m/min).

Assuming that the front edge of the spot overlaps with the front mouth edge of the keyhole [15], the transmission trajectory of the laser beam in the keyhole was drawn according to the actual size of the laser beam and keyhole, as shown in Fig. 2(c). It can be found that only the FKW was exposed to the incident laser beam, and the spot center was the center of the white zone on the FKW. The laser spot center had the highest energy density. Therefore, the most intense evaporation happened in this area. These white zones on the FKW were thus the intense metal evaporation vapor induced by the spot center. The tiny “hollow” at the bottom of the white zone on the FKW was caused by the fact that the intense evaporation recoil pressure in the spot center extruded the molten liquid of the FKW [5]. The reflected light from the tiny “hollow” zone acted on the rear keyhole wall, forming the white metallic vapor on the rear keyhole wall. The phenomenon indicates assumptions that the energy coupling mode in the keyhole was multiple reflection.

Two white zones on the FKW were related to the relatively low frame rate of the high-speed camera, which led to a long exposure time. The frame rate of the high-speed camera was thus increased to 8000 f/s, and a white light attenuator with an optical transmittance of 50% was used to filter the weak light in the keyhole. The obtained results are shown in Fig. 3(a). It can be seen that a white zone on the FKW moved from the top to the bottom of the keyhole, and showed a periodical downward movement with a period of about 0.75 ms. The white zone was the intense laser-induced evaporation vapor on the FKW. The periodical downward movement process of the white zone was thus the dynamic process of the interaction between the laser beam and FKW. According to the keyhole depth and the period of evaporation vapor on the FKW, the calculated downward movement speed of the spot acted on the FKW was between 14 m/s and 21 m/s. This result was comparable to the measured flow-down speed of the molten liquid on the FKW observed by Kaplan et al. [12].
Fig. 3. (a) Typical continuous side morphology of keyhole (8000 f/s, v = 2 m/min), (b) Relationship between the interaction period and welding speed, (c) Typical morphology of keyhole for different welding speeds (8000 f/s).

In addition, Fig. 3(b) presents the relationship between the interaction period and welding speed. The results indicate that the interaction period decreased from about 0.75 ms to about 0.3 ms as the welding speed increased from 2 m/min to 10 m/min. Figure 3(c) shows that the morphology of the keyhole changed with an increasing welding speed. It can be found that the keyhole depth decreased with the increase of the welding speed. And the inclination angle of the FKW decreased also. But the decrease amplitude of the inclination angle was small.

These laser-induced evaporation zones on the front and rear keyhole wall [Fig. 2(b)] are indications for the assumption that the energy coupling mode in the keyhole was multiple reflection. However, only the FKW was exposed to the incident laser beam during welding, and the laser-induced evaporation vapor on the FKW were much larger than the evaporation vapor on the rear keyhole wall. Fabbro et al. measured first absorption of the incident laser on the FKW up to 80% [16]. Therefore, the first absorption on the FKW still dominates the energy absorption. The first absorption of the incident laser on the FKW produced strong evaporation recoil pressure. At the center of the laser spot, the evaporation recoil pressure was maximum. A tiny ‘hollow’ zone was thus produced at the spot center-action region. Under the recoil pressure, the keyhole formation is reminiscent of a periodical drilling process on the FKW by the laser spot center. The drilling direction was along the laser beam direction.

For a further revealing of the periodic behavior of the interaction process between the laser beam and FKW, based on our previously proposed experimental methods and parameters that preserve the keyhole by rapid cooling of the molten pool [7,8], the surface morphology of FKW and its side-morphology were obtained, as shown in Figs. 4(a) and 4(b), respectively. A series of concentric elliptical rings were observed on the middle and upper sections of FKW in Fig. 4(a) (i.e., the laser spot center-action region). This is caused by the Gaussian profile of the laser beam acting on the FKW. A molten layer existed in front of the FKW in Fig. 4(b). Furthermore, the melting front was not a smooth curve: the molten layer was thicker in the middle and upper sections (i.e., the laser spot center-action zone). Based on Fig. 2, Figs. 4(a) and 4(b), a three-dimensional schematic diagram of the interaction between the laser beam and FKW was drawn, as shown in Fig. 4(c).
According to Fig. 4(c), the periodic fluctuation mechanism of the FKW can be explained as follows: Taking into account the energy balance on the FKW, the part of the absorbed laser intensity expended for the material melting $I_m$ can be expressed:

$$I_m = A(\alpha)I_i - I_o - I_v$$  \hspace{1cm} (1)

where $\alpha$ is the angle between the laser beam axis and the normal to the FKW surface (i.e., the inclination angle of the FKW); $A(\alpha)$ is the angle-dependent coefficient absorption of unpolarized laser radiation; $I_i$ is the incident laser intensity at the FKW surface; $I_o$ is the part of the absorbed laser intensity expended for the energy loss due to the heat conduction; $I_v$ is the part of the absorbed laser intensity expended for the melt vaporization, and can be ignored [17]. Considering the energy flux balance in the FKW, the drilling velocity along the laser beam direction on the FKW $v_d$ can be written as [5]:

$$v_d = \left\{ \frac{\alpha \rho_s}{r_s \rho_m} \left[ \frac{2}{\rho_m} \left( A(\alpha)I_i - \frac{\kappa}{a} u (T_i - T_m) \right) \frac{v_T - \sigma}{L_v r_s} \right] \right\}^{1/2} \cos(\alpha) \hspace{1cm} (2)$$

where $\kappa$ is the heat conductivity, $a$ is the heat diffusivity, $\rho_s$ is the solid metal density, $\rho_m$ is the melt density, $r_s$ is the beam radius, $T_i$ and $T_m$ are the boiling and melting temperatures, correspondingly, $u$ is the welding speed, $v_T$ is the near-surface vapor velocity, $L_v$ is the latent heat of vaporization and $\sigma$ is surface tension coefficient.

The Brewster angle of the wavelength of 1070 nm on the FKW of iron at boiling temperature is about 81° [11]. And the inclination angle of the FKW was approximately 85° in Fig. 2. When $\alpha$ nears the Brewster angle on the FKW, the $A(\alpha)$ will reach a maximum.
value. According to Eqs. (1) and (2), $I_m, I_o$ and $v_d$ will increase, especially in the laser spot center action-zone. The evaporation recoil pressure, induced by the spot center on the FKW, drives down the melt in the form of the drilling \[5,11,12\]. This will result in the increase of $\alpha$. Therefore, $\Delta(\alpha), I_m$ and $v_d$ decrease due to the increase of $\alpha$. Subsequently, the $\alpha$ will decrease again, and nears the Brewster angle again owing to the relative motion between the laser beam and welded material. This may be the reason that the periodical interaction process between the spot center and the FKW happened. According to the ‘runaway’ instability theory of the FKW \[5\], an increase in the welding speed will result in an increase in the frequency of tiny ‘hollow’ formation (i.e., the laser spot center-action region on the FKW). The laser drilling period (drilling time) on the FKW thus decreased with the increase of the welding speed.

4. Summary

In summary, through observing the laser-induced intense evaporation vapor on the keyhole wall, this work shows assumptions for the interaction processes between the laser beam and keyhole wall during high-power fiber laser welding. Only the FKW was exposed to the incident laser beam during welding. The evaporation vapor induced by the spot center on the FKW moved downward with a period of about 0.3-0.75 ms. A tiny ‘hollow’ zone was produced at the spot center-action region on the FKW. The keyhole formation process during welding is reminiscent of a periodical drilling process of the spot center on the FKW. The drilling direction was along the beam direction. Some evaporation vapor on the rear keyhole wall, induced by the reflected light from the FKW, suggest the assumption that the laser energy coupling mode in keyhole was multiple reflection. And the keyhole depth was mainly decided by the drilling behavior induced by the first absorption of the FKW.

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