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Fresnel absorption and inverse bremsstrahlung absorption in an actual 3D keyhole during deep penetration CO_2 laser welding of aluminum 6016

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ABSTRACT

An actual keyhole is captured by a high-speed camera during deep penetration laser welding of aluminum alloy 6016. With the help of spectrograph, plasma spectra are acquired, and then after Abel transformation, electron temperature is calculated. Through Lorenz nonlinear fitting, the FWHM of Stark broadening lines is obtained to compute electron density. To know more about the mechanism of deep penetration laser welding, both the effect of Fresnel absorption and inverse bremsstrahlung absorption of plasma on the laser power distribution is considered. Results indicate that electron temperature is very unstable in the keyhole which has a declining tendency in the radius direction, electron density increases in the depth direction while it does not change too much along radius. Laser intensity absorbed on the keyhole wall through Fresnel absorption is hardly uniform and distributes mainly on the front wall and the bottom of keyhole wall, and inverse bremsstrahlung absorption of keyhole plasma plays a dominant role in absorbing laser power compared with Fresnel absorption.

1. Introduction

When laser beam with high laser intensity ($>10^6$ W/cm^2) incidences workpiece, the irradiated material is vaporized, then a keyhole is formed. The formation of keyhole is indispensable to the deep penetration laser welding. The keyhole is filled with plasma when welding metal like aluminum alloys. The energy-coupling mechanism known as keyhole effects, which can be mainly divided into Fresnel absorption and inverse bremsstrahlung absorption of plasma, has played an important role in melting the metal material and keeping the keyhole stable.

As well-known, much effort has been dedicated to keyhole effects. In 1989, considered both Fresnel absorption and inverse bremsstrahlung absorption of plasma, Dowden et al. [1] analyzed the laser-plasma interaction in laser keyhole welding. Their results indicated that both Fresnel absorption at the keyhole walls and inverse bremsstrahlung absorption of plasma played important roles. But they used a simple uniform laser line source. In 1990, Finke et al. [2] carried out one-dimensional calculation with a cylindrical keyhole and pointed out that energy transferred from plasma to workpiece due to the release of kinetic and recombination energies of electron-ion pairs is more effective than that by heat conduction at the surface of the material under their conditions. 1993, Simon [3] considered the above two absorption mechanisms with a cylinder model. In 1994, Kaplan [4] indicated that plasma absorption was much lower than Fresnel absorption in CO_2 laser welding of mild steel. In 1994, based on the spectroscopic measurements of laser induced plasma during laser welding of stainless steel, Szymański [5] calculated the electron temperature and density, and then computed the plasma absorbility of the CO_2 laser beam, but he found no significant laser absorption in the plasma over the metal surface. In 1997, Solana and Negro [6] used an axisymmetrical keyhole model to analyze keyhole profiles and laser intensity distributions with depth for laser beam with Gaussian and uniform top-hat distribution respectively, and studied the effect of multiple reflections inside the keyhole with a free boundary. In 2000, Fabbro and Chouf [7] began to study multiple reflections inside the keyhole by tracing a ray of light. The keyhole was assumed to be rotationally symmetric. But it is not the case. In practical deep penetration laser welding, especially in high speed penetration laser welding, the keyhole shape [8] is not rotationally symmetric. So their results may have great difference from reality.

In 2002, Jin et al. [9] used an improved set-up and specially-selected transparent material (GG17 glass, a Chinese brand of glass similar to Pyrex glass) to observe the keyhole shape. Based on a so-obtained keyhole picture, Jin et al. determined the keyhole profile by means of polynomial fitting. Then, according to geometrical optics, Jin et al. traced a ray of light in the keyhole, and calculated the laser intensity absorption on the front and rear keyhole wall. In 2006 and 2008, under the assumption of circular and elliptical cross-section of the keyhole at each keyhole depth respectively, Jin et al. [10,11] reconstructed the 3D bending keyhole, and studied multiple reflections and Fresnel absorption in the actual 3D keyhole during deep penetration laser welding.

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The results of Jin et al.s' above work indicated that laser intensity absorbed through Fresnel absorption is uneven distributed on the keyhole walls and mainly absorbed on the front keyhole wall. In all of Jin et al.s' above work, GG17 glass was used as the workpiece material to be welded, no plasma was existed during laser welding. So they considered only Fresnel absorption in the process of laser welding.

Plasma in the keyhole plays an indispensable role in laser welding metal materials, which can improve energy coupling between the laser beam and the target. Under the assumption of conical keyhole, Jin et al. [12] studied inverse bremsstrahlung absorption of keyhole plasma in deep penetration laser welding. Their result showed that the total laser intensity absorbed on keyhole wall through inverse bremsstrahlung absorption of plasma in the keyhole depends primarily on the first 3 times reflection. On the top of keyhole, the absorbed laser intensity is mainly decided by inverse bremsstrahlung absorption of keyhole plasma, while on the bottom of keyhole, the absorbed laser intensity is mainly determined by Fresnel absorption of multiple reflections. Using specially-designed set-up with a so-called 'sandwich' sample, Zhang [13] pointed out that the keyhole plasma had a considerable effect on the energy-transferred efficiency of the incident laser beam to the material. In 2010, Li et al. [14] studied the radiation of a Nd:YAG Laser-MIG hybrid plasma. Their results showed that the electronic temperature of the Laser-MIG hybrid welding arc is a little higher than that of the MIG, and the electronic density of Laser-MIG hybrid welding is higher than that of the MIG. In all of the above articles, only qualitative analysis about the influence of laser induced plasma on the laser welding process were made.

Based on an experimentally-obtained keyhole and experimentally-observed spectra of keyhole plasma, the electron temperature, the electron density and the inverse bremsstrahlung absorbility of keyhole plasma during deep penetration laser welding of aluminum alloy 6016 are calculated in this paper. Then, the laser intensity absorbed on the keyhole wall through Fresnel absorption and inverse bremsstrahlung absorption of keyhole plasma respectively is computed. Finally, the roles of multiple reflections on the keyhole wall and the keyhole plasma are quantitatively analyzed.

2. Experimental procedures

2.1. Direct observation of keyhole

The experimental set-up used to observe the keyhole shapes during laser welding aluminum alloy, is shown in Fig. 1. The specially-designed sample is consisted of two parts: One is made of GG17 glass [10], the main composition of which is SiO_2, which is hard to form plasma and the vapor of which is transparent to the CO_2 laser beam. The other one is made of aluminum alloy 6016, the composition of which is shown in Table 1. The thickness of aluminum alloy 6016 sheet is 0.8 mm. A high-speed camera is used to take photographs of keyholes from the vertical direction to the welding velocity.

With this set-up used, a keyhole picture can be obtained as shown in Fig. 2. The welding conditions are as follows: the welding velocity is 1 m/min, the incident CO_2 laser power is 2 KW, the total flow of coaxial and lateral flow is 15 L/min, the defocus is 0 mm, and the focal diameter is 0.4 mm.

2.2. Direct spectral observation of keyhole plasma

The experimental set-up used to observe the spectra emitted from the keyhole plasma during laser welding aluminum alloy is shown in Fig. 3. The sample used is the same as that used in Fig. 1. Instead of a high-speed camera used, a spectrometer system made by Princeton Instruments Company U.S, which contains a SpectraPro-2356 model spectrograph with such technical parameters as shown in Table 2 and a PIXIS (400F area-array CCD of 1340×400 pixels, and special optical fiber bundles), is used to observe the spectra of keyhole plasma. In our experiment, the exposure time is 0 millisecond, the readout time is 45.3187 millisecond and the grating chosen is 1200 g/mm.

With this set-up used, the spectra of keyhole plasma at different point can be obtained. Fig. 4 shows one of such diagrams of special spectra. The welding conditions used are the same as those used in Fig. 1.

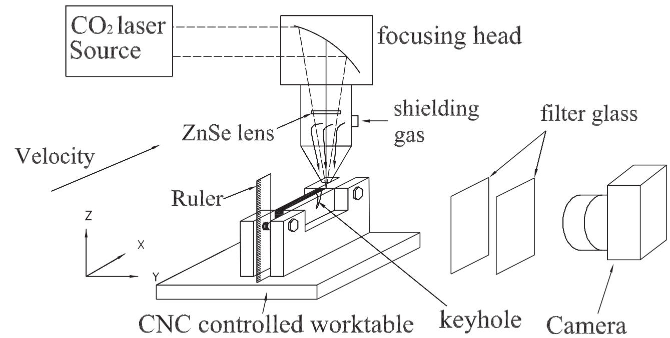

Fig. 1. Experimental set-up for keyhole observation.

Table 1
The composition of aluminum alloy 6016.

Composition	Content (%)	Composition	Content (%)
Si	1.0–1.5	Cr	≤ 0.1
Fe	≤ 0.5	Zn	≤ 0.2
Cu	≤ 0.2	Ti	≤ 0.1
Mn	≤ 0.2	Al	Surplus
Mg	0.25–0.6	Others	≤ 0.15

3. Theoretical calculation

3.1. Reconstruction of 3D keyhole

Following the same way as that used in the reference [10], the keyhole profile can be obtained as shown in Fig. 5(a) by means of polynomial fitting. Then, under the assumption of circular section of the keyhole at each keyhole depth, a 3D keyhole can be reconstructed as shown in Fig. 5(b). The diameter of the keyhole at its mouth is around 0.23 mm, and the depth of the keyhole is about 4.5 mm.

The keyhole profile can be described as follows:

For the front keyhole wall:

$$F_f(z)=a_1z^3+a_2z^2+a_3z+a_4$$

For the rear keyhole wall:

$$F_r(z)=b_1z^3+b_2z^2+b_3z+b_4$$

where a_1-a_4 and b_1-b_4 are the polynomial coefficients of the front and rear keyhole wall, respectively. The values of them are shown as follows:

$$a_1=9311.387528,\quad a_2=21.464023,$$
$$a_3=0.078300,\quad a_4=0.000123;$$