Energy absorption characteristics in high-power fiber laser welding and active control of plume

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Molten pool and plume are both inherent physical phenomena in high-power fiber laser deep penetration welding. Among them, the molten pool is the main site for optical-thermal energy conversion, while the plume has a significant negative impact on the welding process. In this paper, the conversion and absorption of optical-thermal energy during welding were studied. With the radius of the laser spot decreasing gradually, the total absorptivity of the incident laser of the material first decreases and then increases. In addition, this paper presents a novel idea of micro-beam high-speed shielding gas flow (coaxial double-layer shielding gas nozzle). In this design, the inner layer delivers a micro-beam high-speed shielding gas flow that regulates the formation of plume, while the outer layer supplies a low-speed and wide-range shielding gas flow for shielding the molten pool. This new micro-beam high-speed shielding gas flow can significantly inhibit the formation of plume and spatter, markedly enhances the surface quality of the weld seam, increases the penetration depth of the weld.

Keywords: Laser welding; Absorption; Plume; Active control; Shielding gas.

1. Introduction

Laser welding, as an advanced connection technology that has risen rapidly in recent years, has greatly changed the limitations of traditional manufacturing with its high precision, high efficiency and high adaptability [1]. The core of laser welding technology is to use photothermal effect to process materials. In laser welding, the absorption of incident laser by materials is easily influenced by factors such as the surface state of materials and processing parameters [2]. In laser keyhole welding, the laser will go deep into the keyhole, and the energy coupling will be completed in the keyhole through multiple reflection and absorption of the keyhole wall and the reverse ductile absorption of the plasma in the keyhole [3].

As an inherent physical phenomenon in the process of high-power fiber laser welding, the speed of plume ejected from the keyhole can reach tens of meters per second [4]. Particles in the plume will also attenuate the energy of incident fiber laser, which will seriously affect the transmission of laser energy and the stability of welding process [5]. Therefore, in order to effectively control the plume and not have a negative impact on the molten pool, it is necessary to design a new type of shielding gas flow that can not only blow off the plume in the focused laser beam, but also not disturb the molten pool.

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In this paper, we have studied the changing law of absorptivity of metal materials under different processing modes. Then, the idea of adding microbeam high-speed shielding gas in the middle of conventional inert shielding gas is put forward. The research results can not only enrich the basic theory of laser welding, but also have important guiding significance for optimizing laser welding technology and improving welding quality.

2. Methods

2.1. *Experimental installation*

IPG YSL-6000 fiber laser was selected in the experiment, with rated output power of 6 kW and emitted laser wavelength of about 1070 nm. The beam focusing parameter K_f =8 mm·mrad, the core diameter of transmission fiber is 200 μm, the focal length of output coupling collimator is 200 mm, and the focal length of focusing mirror is 300 mm. In the laser welding test, Q235 low-carbon steel plate with the size of 100 mm×50 mm×10 mm was used for flat scanning.

2.2. *Nozzle design*

The plume in the focused laser beam can be effectively regulated and controlled without negative influence on the weld pool, and the shielding gas flow needs to have dual effects of blowing off the high-speed plume and acting on the weld pool with small force. Therefore, this paper puts forward a double-layer composite airflow protection idea that the inner layer is filled with high-speed micro-beam airflow and the outer layer is filled with conventional shielding gas: that is, a coaxial double-layer shielding nozzle is developed, in which the inner layer nozzle generates micro-beam high-speed shielding gas and only blows away the plume in the beam, and the outer layer nozzle outputs shielding gas to protect the welding pool. The nozzle structure is shown in Fig.1.

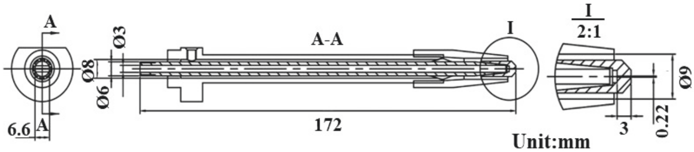

Fig. 1. Schematic diagram of double-layer nozzle structure

A high-speed camera shooting device was built to observe the dynamic behavior of plume. During the observation, the high-speed camera was parallel to the machining plane to ensure that the plume eruption during welding was completely within the camera's monitoring field of vision, and the shooting frame rate was 10000 fps.

3. Results and discussion

3.1. *Effect of laser spot size change on material absorptivity*

The output power of the fixed fiber laser was 3 kW and the scanning speed was 2 m/min.

The trial-and-error method proposed by our research group was used to obtain the absorption rate of the incident laser at different spot sizes [6], that is, the temperature field of the molten pool was obtained by numerical simulation. When the melting point isotherm in the temperature field matches the fusion line in the cross section of the weld well, the absorption rate set in the numerical simulation is regarded as the absorption rate of the plate to the incident laser. The calculation result is shown in Fig. 2. With the decrease of laser spot size, the absorption rate shows a trend of first decreasing and then increasing. This is related to the increase of the power density, the shortening of the solid-state time of the material, the reduction of the solid-phase region in the laser region, and the mirror-like reflection on the surface of the molten pool [7].

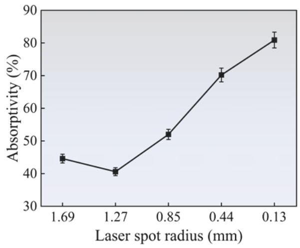

Fig. 2 Influence of changing laser spot radius on absorptivity

When the laser spot continues to shrink, the absorptivity changes from decreasing to increasing. When the laser spot radius is reduced to 0.44 mm, the processing mode has changed to keyhole processing mode, and the absorption rate has jumped from 52% to 70.2%. This phenomenon shows that the depression shape of the gas-liquid interface of the molten pool has a significant influence on the absorption behavior of laser energy during laser welding: when the depression shape of the gas-liquid interface of the molten pool is not obvious, the mirror-like reflection of the molten pool leads to the lowest absorption rate; With the gradual deepening of the depression of the gas-liquid interface of the molten pool and even the formation of deep keyhole, the absorptivity will also increase (the depressed molten pool will converge the incident laser [8]).

3.2. *Active control effect of micro-beam high-speed shielding gas on plume*

When the laser power is fixed at 6 kW, the welding speed is 2 m/min, the defocusing amount is 0 mm, and the outer shielding gas flow rate is fixed at 10 L/min, only the inner microbeam high-speed shielding gas flow rate is changed, the plume morphology obtained is shown in Fig. 3. It can be seen that when the microbeam high-speed shielding gas (flow rate is 0 L/min) is not applied, the generated plume consists of a bright swinging plume at the bottom and a long and narrow plume with the upper laser beam focused. In addition, there are a large number of observable spatter particles in the outer space of plume. With the increase of microbeam high-speed shielding gas flow rate (1~5 L/min), the upper long and narrow plume gradually disappears, leaving only a small amount of bottom swinging plume, and the number of spatter particles is relatively small.

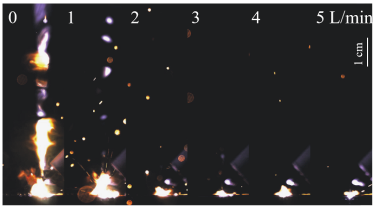

Fig. 3. The shape of the plume under different flow flux of micro-beam high-speed shielding gas.

3.3. *Active control effect of micro-beam high-speed shielding gas on weld forming*

Fig. 4(a) shows the surface morphology of the weld when different micro-beam high-speed shielding gas flow. It can be seen that the forming quality of weld surface first increases and then decreases with the increase of micro-beam high-speed shielding gas flow. When the micro-beam high-speed shielding gas flow is not applied, the weld surface roughness is poor and there is obvious spatter phenomenon. After applying a proper amount of micro-beam high-speed shielding gas flow (1~2 L/min), the weld surface becomes smooth, and the number of spattered particles is obviously reduced. However, when the shielding gas flow rate of micro-beam high-speed protection exceeds 3 L/min, the forming quality of weld surface becomes obviously worse, and the phenomena of undercut and hump increase.

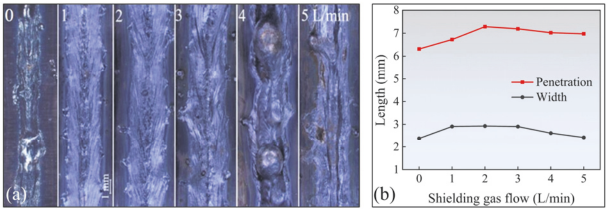

Fig. 4. (a) Weld surface forming under different flow; (b) The penetration depth and width under different shielding gas flow rates.

With the increase of micro-beam high-speed shielding gas flow, the penetration depth and width of weld first increase and then decrease (as shown in Fig. 4(b)). When the flow rate of micro-beam high-speed shielding gas is 2 L/min, the weld penetration and width are the maximum, which are about 15.4% and 22.7% higher than those without micro-beam high-speed shielding gas. However, when the flow rate of micro-beam high-speed shielding gas exceeds 3 L/min, the penetration depth and width of weld gradually decrease.

The influence of shielding gas flow on welding process is reflected in the impact and pressure on particles such as plume and spatter, and the isolation of external air to avoid oxidation of molten pool. In the double-layer nozzle developed in this paper, the gas flow generated by the outer circular nozzle has a wide range and a slow flow rate, which can play a role in protecting the molten pool. The micro-beam high-speed shielding gas flow generated by the inner slit nozzle is mainly used for blowing away the plume in the focused laser beam with small range and high flow rate. However, according to Fig. 4, the adoption of micro-beam high-speed gas flow will still have a certain impact on the molten pool. This shows that the micro-beam high-speed gas designed in this paper is not the optimal shape, and the related work still needs further research.

4. Conclusion

This paper discusses the influence of laser spot size on the absorptivity of incident laser in laser welding process. Then, the feasibility of a new double-layer composite shielding gas method is explored, and the main conclusions are as follows:

(1) With the radius of the laser spot decreasing gradually, the total absorptivity of the incident laser of the material first decreases and then increases;

(2) A coaxial inner nozzle capable of generating micro-beam high-speed shielding gas can be designed inside the conventional protective nozzle. When the flow rate of micro-beam high-speed shielding gas flow is 2 L/min, the plume can be effectively controlled and the weld penetration depth can be improved.

(3) Compared with the conventional shielding gas flow, the composite shielding gas flow proposed in this paper can obviously improve the protective effect shielding gas, but the optimal characteristics of micro-beam shielding gas flow need further study.

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References

1. Cui, S., Pang, S., Zhang, S., Liao, Y. and Cai, H. Influence of Different Welding Parameters on the Morphology, Microstructure, and Mechanical Properties of 780 Duplex-Phase Steel Laser Lap Welded Joint. *Materials* **15**, 3627 (2022).
2. Niu, C., Zhu, T. and Lv, Y. Influence of Surface Morphology on Absorptivity of Light-Absorbing Materials. *International Journal of Photoenergy* **2019**, 1–9 (2019).
3. Coviello, D., D'Angola, A. and Sorgente, D. Numerical Study on the Influence of the Plasma Properties on the Keyhole Geometry in Laser Beam Welding. *Front. Phys.* **9**, 754672 (2022).
4. Zou, J. L. Huang Z. H., Gong J J, Zhao Y, Wang Z and Wu Q. Characterization of micron-sized particles in the focused laser beam during fiber laser keyhole welding. *Optics & Laser Technology* **156**, 108463 (2022).
5. Lee, S.-J., Katayama, S., Kim, J.-D. and Suh, J. The Effect of Plume Generated on the Microstructural Behavior of the Weld Mixed Zone in High-Speed Laser Dissimilar Welding. 14 (2021).
6. Xie, S. Zhu B Q, Qiao J N, Zhuang Y and Zou J L. Molten pool air-liquid interface in high-power laser manufacturing: Evolution law and energy absorption characteristics. *Surfaces and Interfaces* **41**, 103214 (2023).
7. Simonds, B. J. Sowards J, Hadler J, Pfeif E, Wilthan B, Tanner J, Harris C, Williams P and Lehman J. Time-Resolved Absorptance and Melt Pool Dynamics during Intense Laser Irradiation of a Metal. *Phys. Rev. Applied* **10**, 044061 (2018).
8. Zou, J. L., He, Y., Wu, S. K., Huang, T. and Xiao, R. S. Experimental and theoretical characterization of deep penetration welding threshold induced by 1-μm laser. *Applied Surface Science* **357**, 1522–1527 (2015).