Optics and Lasers in Engineering 100 (2018) 239–247

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Vapor plume oscillation mechanisms in transient keyhole during tandem dual beam fiber laser welding

Xin Chen[1], Xiaosi Zhang[1], Shengyong Pang*, Renzhi Hu, Jianzhong Xiao

State Key Laboratory of Material Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Keywords:
Vapor plume
Oscillation mechanism
Dual beam
Fiber laser welding
Dynamical keyhole

ABSTRACT

Vapor plume oscillations are common physical phenomena that have an important influence on the welding process in dual beam laser welding. However, until now, the oscillation mechanisms of vapor plumes remain unclear. This is primarily because mesoscale vapor plume dynamics inside a millimeter-scale, invisible, and time-dependent keyhole are difficult to quantitatively observe. In this paper, based on a developed three-dimensional (3D) comprehensive model, the vapor plume evolutions in a dynamical keyhole are directly simulated in tandem dual beam, short-wavelength laser welding. Combined with the vapor plume behaviors outside the keyhole observed by high-speed imaging, the vapor plume oscillations in dynamical keyholes at different inter-beam distances are the first, to our knowledge, to be quantitatively analyzed. It is found that vapor plume oscillations outside the keyhole mainly result from vapor plume instabilities inside the keyhole. The ejection velocity at the keyhole opening and dynamical behaviors outside the keyhole of a vapor plume both violently oscillate with the same order of magnitude of high frequency (several kHz). Furthermore, the ejection speed at the keyhole opening and ejection area outside the keyhole both decrease as the beam distance increases, while the degree of vapor plume instability first decreases and then increases with increasing beam distance from 0.6 to 1.0 mm. Moreover, the oscillation mechanisms of a vapor plume inside the dynamical keyhole irradiated by dual laser beams are investigated by thoroughly analyzing the vapor plume occurrence and flow process. The vapor plume oscillations in the dynamical keyhole are found to mainly result from violent local evaporations and severe keyhole geometry variations. In short, the quantitative method and these findings can serve as a reference for further understanding of the physical mechanisms in dual beam laser welding and of processing optimizations in industrial applications.

1. Introduction

The dual beam laser welding process can reduce defects such as porosity and spatter, obtain better surface forming quality, and improve gap adaptability, compared with single beam processes. Therefore, it has been widely used in industries such as the manufacturing of automobiles, ships, and aerospace equipment. However, explanations of the physical mechanisms of dual beam laser welding have obviously lagged behind practical applications, especially for vapor plume dynamics inside the keyhole. Thus, very limited knowledge of the vapor plume dynamical mechanism is available to optimize the weld quality in dual beam laser welding.

Previous research has mainly focused on the investigations of defect reduction and process optimization through experiments in dual beam laser welding. For example, Xie [1] observed that centerline cracking susceptibility, as well as weld spatter and weld hardness, were reduced in steel welds during the CO_2 laser welding process. Shibata et al. [2] found that aluminum car body panels can be stably welded at high speed. They suggested that large ratio of the keyhole depth to keyhole opening could cause the formation of porosity defects. Haboudou et al. [3,4] found that the porosity rate was largely reduced when using dual beam techniques in 5083 aluminum alloy laser welding. They argued that the reduction in porosity resulted from the stability of the dual beams on the weld pools and keyhole dynamics. Capello and Previtali [5] argued that the reasonable related-process parameters used in dual beam welding, such as inter-beam distance and feed rate, can efficiently reduce the pore area. Yan et al. [6] also found that, by using the dual laser beam method, porosity defects can be obviously reduced or eliminated in the lap welded joints of steel/aluminum alloys. However, the dynamical behaviors of the transient keyhole and vapor plume are difficult to quantitatively investigate using current experimental methods.

Recently, many simulations have been carried out to understand the process of dual beam laser welding. Hu and Tsai [7] numerically observed the oval shape of a weld pool by using a computational fluid dynamics model. Zhou et al. [8,9] studied the dynamical behaviors of a

* Corresponding authors.
E-mail address: spang@hust.edu.cn (S. Pang).
[1] Co first author.

http://dx.doi.org/10.1016/j.optlaseng.2017.09.010
Received 20 July 2017; Received in revised form 6 September 2017; Accepted 7 September 2017
Available online 14 September 2017

Table 1
Main process parameters used in the experiments and simulations.

Process number	Inter-beam distance (mm)	Laser power (kW)	Welding speed (m/min)
1	0.6	1.8 + 1.8	2.5
2	0.8	1.8 + 1.8	2.5
3	1.0	1.8 + 1.8	2.5
4	1.2	1.8 + 1.8	2.5

keyhole and weld pool based on a 3D mathematical model. They argued that dual laser beams can increase the keyhole and weld pool size, which can reduce humping defects. Pang et al. [10] numerically investigated the dynamics of a self-consistent keyhole and weld pool and proposed that the process stabilization mechanism is due to the combined action of several physical factors.

Vapor plume behaviors outside the keyhole opening in dual beam laser welding have also been experimentally studied. Xie [1] observed that dual beams could suppress the vapor plume oscillation during the CO_2 laser welding process. Li et al. [11] investigated the oscillation degree of metallic vapor outside the keyhole by analyzing the vapor area variance using high-speed imaging. They found that a vapor plume turns out to be more stable when using dual beams rather than a single beam during the welding process. Very recently, vapor plume behaviors in a dynamical keyhole during single laser welding have been numerically investigated [12,13]. Dynamical characteristics of a vapor plume and its close relationship with keyhole dynamics were analyzed [14,15]. However, the interactions of the keyhole's two tips produced by dual laser beams cause a more complex dynamical behavior compared with single beam welding. Currently, the oscillation mechanisms of a vapor plume in the dynamical keyhole of dual beam laser welding remain unclear.

In this research, we quantitatively investigate the dynamical behaviors and mechanisms of a vapor plume inside keyholes in dual beam laser welding. First, we observe and summarize the vapor plume oscillation behaviors outside the keyhole by using high-speed imaging. We then visualize the evolution of vapor plume behaviors inside dynamical keyholes during the welding process using numerical simulation for the first time, to our knowledge, and present the close relationship between the vapor plume inside and outside the keyhole. Furthermore, we investigate the vapor plume oscillations as a function of dynamical keyhole geometries at different beam distances. Finally, we systematically analyze and discuss the mechanisms of vapor plume oscillations in dual beam laser welding.

2. Methods

To investigate the vapor plume dynamics in dual beam laser welding, the method of direct numerical simulation combined with experiment was used. A short-wavelength (1.07 μm) Gaussian laser beam was used. The laser spot radius was approximately 0.4 mm. The welding material used was a typical 304 stainless steel, whose chemical compositions were given in our previous reports [12,14]. To protect vapor plume dynamics from the effects of shielding gas, no shielding gas was used during the welding process. In addition, we used many process parameters in the welding experiments, and chose four groups (Table 1) from them with which to analyze the dynamical characteristics of the vapor plume under the synergistic reaction of dual laser beams during welding.

Based on our previous 3D transient multiphase model [12], we developed a 3D comprehensive model to study dual beam laser welding. Even though the physical behaviors in dual beam welding are more complex, e.g., oscillations of the keyhole with two tips irradiated by dual laser beams, the physical process (Fig. 1) is quite similar to that of the single one. Specifically, vapor plume fluid flows, as well as keyhole and weld pool dynamics including phase interface evolutions, could be described by our previous 3D transient model [12]. Moreover, the dual laser beams working on a keyhole wall were also captured by a robust ray tracing method [10], even though the exact formula differs from that of a single beam. As a result, in this paper, we have only presented the basic equations of the developed comprehensive model for dual beam laser welding. The fluid flows of an incompressible weld pool (l) and vapor plume (g) were described by incompressible Navier–Stokes equations [12]:

$$\nabla \cdot \boldsymbol{U}_i = 0, \tag{1}$$

$$\rho_i\left(\frac{\partial \boldsymbol{U}_i}{\partial t} + (\boldsymbol{U}_i \cdot \nabla)\boldsymbol{U}_i\right) = \nabla \cdot (\mu_i \nabla \boldsymbol{U}_i) - \nabla p_i + \boldsymbol{F}_i, \tag{2}$$

where $i = l,\ g$, respectively, denote the metallic liquid of the weld pool and the vapor plume. $\boldsymbol{U}$ is the 3D velocity vector, ρ the density, μ the viscosity, and p the pressure. The source term $\boldsymbol{F}_i$ represents the external force action on the fluids. We have $\boldsymbol{F}_l = -\frac{\mu_l}{K}\boldsymbol{U}_l - \frac{C\rho_l}{\sqrt{K}}|\boldsymbol{U}_l|\boldsymbol{U}_l + \rho_l \boldsymbol{g}\beta(T - T_{\mathrm{ref}})$, where the first two terms to the right donate the Darcy term and the third term donates buoyancy force, where K is the Carman–Kozeny coefficient [16,17]. $\boldsymbol{g}$ is the 3D gravitational acceleration vector, β the thermal expansion coefficient, T the temperature, T_{ref} the reference temperature, and C an inertial parameter [16–18]. $\boldsymbol{F}_g = \rho_g \boldsymbol{g}$ represents gravitational force. The heat transfer in the weld pool is described by an energy conservation equation [11,19]:

$$\rho_l C_p\left(\frac{\partial T}{\partial t} + (\boldsymbol{U}_l \cdot \nabla)T\right) = \nabla \cdot (k\nabla T), \tag{3}$$

where C_p is the specific heat capacity and k the heat conductivity of the metallic liquid in the weld pool. The level set (LS) method was used to capture the keyhole free surface evolutions, which can be simply described as follows [20]:

$$\frac{\partial \phi}{\partial t} + \boldsymbol{U}_l \cdot \nabla\ \phi = 0, \tag{4}$$

where ϕ donates a time-varying sign distance function $\phi(\boldsymbol{x}, t)$: $(R^3, t) \rightarrow R$. As mentioned above, during the welding process the expression of the energy density absorptions of the keyhole free surface irradiated by dual laser beams differs from that of single laser beam. The energy density absorptions of a keyhole irradiated by dual laser beams, q, are expressed by the following equation [10]:

$$\begin{aligned} q = {} & I_1(r_1, z_1)(\boldsymbol{I}_1 \cdot \boldsymbol{n})\alpha_{\mathrm{Fr}}(\theta_1) + \sum_{m=1}^{N} I_m(r_1, z_1)\alpha_{\mathrm{Fr}}(\theta_m) \\ & + I_2(r_2, z_2)(\boldsymbol{I}_2 \cdot \boldsymbol{n})\alpha_{\mathrm{Fr}}(\theta_2) + \sum_{k=1}^{N} I_k(r_2, z_2)\alpha_{\mathrm{Fr}}(\theta_k) \end{aligned}, \tag{5}$$

where $I_1(r_1, z_1)$ denotes the first beam energy density distribution and $I_2(r_2, z_2)$ the second. I_m and I_k denote the mth and kth reflections, respectively. $\boldsymbol{I}$ denotes the unit vector of incident beams, θ is the included angle between the incident ray and the corresponding unit normal ($\boldsymbol{n}$) of the keyhole free surface, α_{Fr} represents the coefficient of Fresnel absorption, and N is the incident times of the beams. The detailed ray tracing method and calculation steps of this method can be found in our previous report [10]. In addition, the other governing equations, the detailed boundary conditions, numerical methods, and thermal physical parameters can also be found in Refs. [10,12].

The geometric model used in the simulations is illustrated in Fig. 2. We only used a part of the sample, of size $3.0 \times 1.5 \times 3.0$ mm^3 in the