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# Dynamics of vapor plume in transient keyhole during laser welding of stainless steel: Local evaporation, plume swing and gas entrapment into porosity

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ABSTRACT

In order to better understand the local evaporation phenomena of keyhole wall, vapor plume swing above the keyhole and ambient gas entrapment into the porosity defects, the 3D time-dependent dynamics of the metallic vapor plume in a transient keyhole during fiber laser welding is numerically investigated. The vapor dynamical parameters, including the velocity and pressure, are successfully predicted and obtain good agreements with the experimental and literature data. It is found that the vapor plume flow inside the keyhole has complex multiple directions, and this various directions characteristic of the vapor plume is resulted from the dynamic evaporation phenomena with variable locations and orientations on the keyhole wall. The results also demonstrate that because of this dynamic local evaporation, the ejected vapor plume from the keyhole opening is usually in high frequency swinging. The results further indicate that the oscillation frequency of the plume swing angle is around 2.0–8.0 kHz, which is of the same order of magnitude with that of the keyhole depth (2.0–5.0 kHz). This consistency clearly shows that the swing of the ejected vapor plume is closely associated with the keyhole instability during laser welding. Furthermore, it is learned that there is usually a negative pressure region (several hundred Pa lower than the atmospheric pressure) of the vapor flow around the keyhole opening. This pressure could lead to a strong vortex flow near the rear keyhole wall, especially when the velocity of the ejected metallic vapor from the keyhole opening is high. Under the effect of this flow, the ambient gas is involved into the keyhole, and could finally be entrapped into the bubbles within a very short time ( $<0.2$ ms) due to the complex flow inside the keyhole.


## 1. Introduction

The vapor plume/plasma plume is one of the most important characteristics of deep penetration laser welding. When a high power density laser beam ( $>1.0$ MW/cm$^2$) is acted on a material, the vapor/plasma plume grows from the liquid–vapor interface due to the evaporation of the material, and fulfills into a vapor cavity (also called a keyhole which is produced by the recession effect of recoil pressure) in a microsecond time. Now, it is clear that the dynamics of the vapor/plasma plume flow in the keyhole is closely related to the process stability and weld quality of laser welding. Nevertheless, currently the mechanisms of vapor/plasma plume dynamics in the keyhole are still not very clear, possibly because the vapor/plasma plume inside the keyhole is invisible by naked eyes, and has very high temperature.

Previously, many experimental methods, such as the high-speed CCD camera imaging, optical spectroscopy and acoustic signal monitoring, were heavily used to understand the mechanisms of the metallic vapor/plasma plume behaviors during laser welding. Several important characteristics of the metallic vapor/plasma plume outside the keyhole, such as the average speed of the ejected vapor plume [1], the luminosity of the plasma plume [1,2], the vapor inclination angle [3,4], spectroscopic characteristics of the vapor plume [5], the optical and acoustic signal of the vapor plume [6], the correlation between the plasma plume and the keyhole behaviors [7], etc. have been studied. Since the surface weld pool behaviors such as the real-time boundary [8], flow characters [9], and interactions with the laser beam [10] etc. can be directly observed, the hydrodynamic interactions with vapor plume outside the keyhole can be possibly investigated by the experimental methods [3,7]. However, the information of the

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invisible internal weld pool and vapor plume inside the keyhole is very hard to be experimentally obtained. Until the late 1990s, the rough high speed flow dynamics of the vapor/plasma plume inside the keyhole was firstly investigated by Matsuanwa et al. through using an X-ray transmission imaging method [11]. Recently, several important characteristics of the plasma plume in the keyhole, such as the local evaporation, the optical emission spectrum and the electron temperature, were also successfully experimentally studied by a "sandwich" method [12]. These promising experimental studies have improved our understandings of the basic physical behaviors of the vapor/plasma plume in the laser welding process. However, present experimental methods are difficult to quantitatively measure the two essential characteristics of the metallic vapor/plasma plume, i.e. the velocity and pressure in the keyhole. The quantitative dynamical parameters of the vapor/plasma plume in the keyhole are significant for understanding the thermal and hydrodynamic interactions with the weld pool, and the formation of the major process defects of laser welding, such as porosity and spatters.

Over the past decades, the numerical simulation has been proved to be an efficient method of better understanding the physical process of deep penetration laser welding. The dynamic behaviors of the vapor/plasma plume, such as the temperature, velocity and pressure in the keyhole, were theoretically predicted [13–23]. Earlier models [13–15] usually assumed the keyhole as a simplified fixed profile, for instance a cylinder. Therefore, the prediction results of these models may only roughly represent the quasi-steady nature of the vapor/plasma plume. Later, more delicate models of vapor/plasma plume dynamics based on an analytically calculated keyhole profile [16–19] were proposed. However, the effect of dynamic keyhole evolutions on the behaviors of the vapor/plasma plume in the keyhole was completely neglected. Recently, several promising hydrodynamic models of vapor/plasma plume dynamics in a dynamic keyhole were also proposed. Transient pressure and velocity distributions of the vapor/plasma plume were predicted and its interactions with the keyhole and weld pool were also theoretically simulated [20–23]. Nevertheless, the effect of ambient pressure, which has been known to be a crucial factor for vapor/plasma plume behaviors, were not included in these studies [20–23]. Neglecting this effect would produce significant lower keyhole wall temperature but much higher vapor plume velocity predications [24,25]. Very recently, a novel 3D multiphase model including the ambient pressure effect, which could be used to fully predict the dynamics of the self-consistent keyhole, weld pool and metallic vapor/plasma plume simultaneously, was proposed by the authors [24]. The time-dependent vapor plume pressure and velocity in the keyhole, as well as the transient keyhole profiles and weld pool dynamics were well predicted; good consistencies were obtained with the experimental and literature data.

In this paper, the dynamics of vapor plume inside the transient keyhole in the process of 304 stainless steel deep penetration fiber laser welding is studied by our recently developed 3D multiphase model [24]. The distributions of the keyhole wall temperature, and the velocity and pressure of vapor plume inside the keyhole are quantitatively predicted, and compared with experimental and literature data. The behaviors of the violent local evaporation on the keyhole wall, the plume swing outside the keyhole and the ambient gas entrapment into a bubble are firstly observed by numerical simulations. The mechanisms of these dynamical behaviors of the vapor plume are proposed and discussed.

## 2. Methods

### 2.1. Modeling

In this paper, our previous 3D multiphase model of laser welding [24] was used to simulate the dynamics of the vapor plume in the transient keyhole during deep penetration fiber laser welding of a 304 stainless steel. This model has coupling considered most of the physical factors including the recoil pressure, surface tension, Marangoni shear stress, Fresnel absorption mechanisms, heat transfer and fluid flow in the weld pool and vapor dynamics in the transient keyhole. In the model, the evolution of the keyhole was tracked by Level Set method [26]. The discontinuous liquid–vapor interface was accurately treated by a sharp interface method [27]. The ambient pressure was rigorously incorporated by a novel ambient-dependent surface pressure model [25].

In the theoretical model, the heat transfer and fluid flow behaviors of the incompressible molten liquid in the weld pool are described in [27]:

$$\nabla \bullet \vec{U}_l = 0, \tag{1}$$

$$\rho_l\left(\frac{\partial \vec{U}_l}{\partial t}+(\vec{U}_l \bullet \nabla)\vec{U}_l\right) = \nabla \bullet(\mu_l \nabla \vec{U}_l) - \nabla p_l - \frac{\mu_l}{K}\vec{U}_l - \frac{C\rho_l}{\sqrt{K}}|\vec{U}_l|\vec{U}_l + \rho_l \vec{g}\beta(T-T_{ref}), \tag{2}$$

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

where subscript $l$ represents the molten liquid in the weld pool, $\vec{U}_l$, $\rho_l$, $p_l$, $\mu_l$, $\vec{g}$, $T$, $T_{ref}$, $\beta$, $C_p$, $k$ are respectively represent the three dimensional velocity vector, density, pressure, viscosity, gravitational vector, temperature of weld pool, reference temperature, thermal expansion coefficient, thermal capacity and thermal conductivity. $C$ is an inertial parameter related to the liquid

**Table 1**
Process parameters for deep penetration fiber laser welding of 304 stainless steel.

| Process no. | Laser power (kW) | Welding speed (m/min) | Beam radius (mm) | Shielding gas (L/min) |
|---|---|---|---|---|
| 1 | 1.0 | 3.0 | 0.2 | 0.1 |
| 2 | 1.5 | 3.0 | 0.2 | 0.1 |
| 3 | 2.0 | 3.0 | 0.2 | 0.1 |

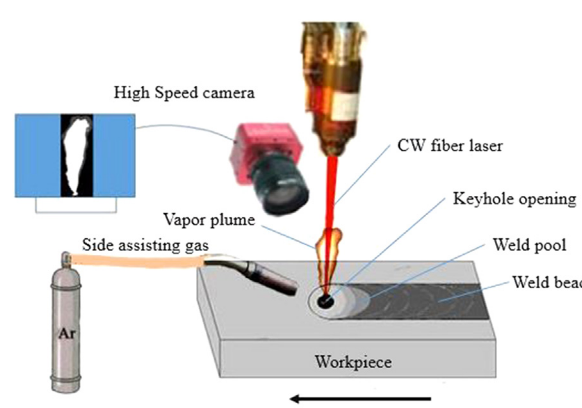


**Fig. 1.** The schematic of experimental setup: fiber laser welding with inti-time high speed camera observations.