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Efficient multiple time scale method for modeling compressible vapor plume dynamics inside transient keyhole during fiber laser welding

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ABSTRACT

Efficient coupling modeling of multiple time scale interactions between keyhole, weld pool and compressible vapor plume during laser welding has long been limited. To address this problem, we present a highly efficient multiple time scale method combining a novel dual-time stepping and Ghost Fluid interpolation strategy with incompressible and compressible fluid solvers, which allows us predicting the compressible plume dynamics inside transient keyhole in fiber laser welding for the first time. In our method, the compressible dynamic vapor inside the transient keyhole is solved with a Roe scheme based algorithm and the incompressible molten liquid of weld pool is calculated by a Projection method. A novel temperature dependent boundary condition of vapor plume is also proposed for the consideration of the dynamic evaporation phenomena on the transient keyhole wall. It is found that the time dependent distributions of vapor plume characteristics, including temperature, pressure, velocity, density and Mach number distributions inside the transient keyhole induced by laser welding can be reasonably predicted by comparing to experimental and literature data. It is also shown that the proposed multiple time scale method is around 60 times faster than the vapor plume modeling method using a single nanosecond scale time step. For the vapor plume in a typical fiber laser welding process, the results indicate that the peak pressure can be greater than 2.0 atmospheric pressures; the average density is around 0.15–0.3 kg/m^3 which is much smaller than the air density; and the local Mach number can be greater than 0.8 or even 1.0 Mach which demonstrates the necessity to treat the vapor plume as a compressible fluid.

1. Introduction

In deep penetration laser welding, the keyhole, weld pool and metallic vapor plume or plasma behaviors are self-consistently associated [1,2]. These coupling behaviors are closely related to the formation of major process defects, such as spatter and porosity. Therefore, understanding the self-consistent dynamics of keyhole, weld pool and vapor plume has received great attentions over the past decades [3–12].

Nevertheless, until now the physical phenomena of laser welding are still not well understood. One of the least known phenomena, probably, is the vapor plume dynamics inside the transient keyhole occurring in laser welding. The reasons mainly lie in the inherent physical characteristics of metallic vapor flow: high temperature, transient, invisible by naked eye, and mesoscale. These challenges make it very difficult for direct experimental investigations. On the other hand, the necessary time scale of keyhole modeling is about microsecond (10^{-6} s) magnitude, but that of metallic vapor modeling is nanosecond (10^{-9} s) magnitude. This crossing time scale problem, and the complex thermal and mechanical boundary conditions on the vapor–liquid interface, also makes it to be challenging for theoretical simulations.

Previously, researchers have made many attempts to study vapor plume via experimental methods. One of the effective ways for this purpose is by vision-based observations. The high speed imaging cameras have been used to reveal the dynamic changes of vapor plume for nearly 20 years [13–15], but this method usually limits to the plume outside the keyhole. Recently, a novel experimental method, called as a sandwich method, has been proposed to observe dynamic vapor plume inside keyhole with the help of high speed imaging; and by this method several characteristics of vapor plume inside the keyhole, such as the electron temperature, were experimentally estimated [16–18]. Besides, non-contact sensing methods based on optical, acoustical and plasma charge signals etc. were also proposed to indirectly diagnose the keyhole and vapor plume characteristics; and some of them have even been

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shown to be able to online monitor typical welding process defects [19]. In past decades, researchers from Osaka University have been developing an X-Ray transmission imaging system for laser welding process, and have applied it to observe the keyhole, molten pool and vapor plume behaviors simultaneously [20–24]. It was shown that the velocity of vapor plume inside keyhole is very high, and its ejection orientation is oscillating, in addition its dynamic characteristics are closely related with the keyhole behaviors. Despite aforementioned advances have been made in past decades, experimental investigations of vapor plume dynamics inside the keyhole are still very challenging, because the resolutions of the obtained results are usually limited.

In recent years, theoretical simulations have been increasingly used in the investigation of vapor plume dynamics inside the keyhole. The major challenges for simulations are tracking the dynamic keyhole profiles, and finding suitable boundary conditions for vapor plume dynamics, especially when the vapor plume is treated as a compressible fluid. Earlier researchers in this direction assumed the keyhole as a simplified fixed geometry, for example a cylinder, a cone or even a line. Then, the vapor pressure distribution and vapor flow velocity inside the keyhole has been simulated; and some rough data of vapor characteristics, such as velocity and pressure, are predicted [25–27]. More elaborate keyhole geometries, analytically determined as a function of main operating parameters such as welding speed, laser incident intensity and sample material, were also used as inputs for vapor plume modeling [28–31]. Steady-state two dimensional incompressible or compressible vapor dynamics inside these static geometries have been studied [28–31]. Modeling of vapor plume dynamics based on transient keyhole profiles in laser welding has also been demonstrated recently [1,32]. To mitigate the computational cost, an unphysical enlargement of vapor plume density was usually utilized in these theoretical studies, so that a larger time step could be used. For example, in Refs. [1,32] the density was set to be 10 kg/m^3 that are approximately two order magnitudes larger than the expected real density. Moreover, the vapor plume was usually assumed as an incompressible fluid, as in such a case the boundary condition for plume dynamics can be greatly simplified, and the computational effort can be further reduced. Even so, the computational cost of these simulations is still rather expensive due to the complexity of physics considered [32]. The attempt works to study the compressible vapor plume dynamics inside transient keyhole also have been made by some research groups. For example, Amara et al. [48] simulated the compressible vapor flow dynamics and found that the compressible vapor friction has some effects on the melt bath wall. However, the boundary conditions in their model seems not suitable to other situations, since the evaporation was assumed to occur only on the front keyhole wall, and the front keyhole is assumed to be fixed. Very recently, Tan et al. [49] presented a multiphase model of keyhole, weld pool and compressible vapor plume by incorporating the assisting gas effect and found the vapor friction and assisting gas play significant effects on keyhole dynamics. However, in their model the effect of ambient pressure seemed to be not taken into consideration, which was demonstrated to be an important factor for accurately modeling the keyhole temperature and vapor velocity in laser welding [38,51]. Besides, the important characteristics of compressible vapor plume, such as vapor density, and Mach number distributions, were not mentioned in their work. More efforts are still needed to model the compressible vapor plume dynamics in transient keyhole during laser welding.

In this paper, we present a highly efficient numerical method for theoretical modeling the compressible vapor plume dynamics inside transient keyhole induced by fiber laser welding. The proposed method overcomes the multiple time scale difficulty of keyhole and vapor plume simulations, in an even more rigorous physical context that free of incompressible assumptions and artificial enlargement of density. Our method features a dual-time stepping and Ghost Fluid interpolation strategy with incompressible Navier–Stokes and compressible Euler solvers. A novel temperature dependent kinetic boundary condition of vapor plume is also first proposed for rigorous considering the dynamic evaporation phenomena on the transient keyhole wall. The implementation of the proposed multiple time scale method is given in detail. Time dependent distributions of temperature, density, and pressure and Mach number inside transient keyhole are successfully predicted with this method, and evaluated by comparing with theoretical and experimental data.

2. Coupling model of keyhole, weld pool and vapor dynamics

2.1. Metallic vapor flow compressibility

In laser welding, the vapor plume is located in a microscale keyhole and produced by evaporation induced by laser ablation. It has been suggested that there are many dynamic humps located on the keyhole wall [2,5,33]. The temperature of the top part of humps would exceed the boiling point more than several hundred degrees due to the direct irradiance of laser beam, whereas that of the bottom parts would be much lower than the boiling point. Hence, there might be large pressure difference inside the keyhole. Previous theoretical calculation suggested that the peak velocity of vapor plume, induced by that difference, could be greater than 300 m/s [30]. Therefore, it may be reasonable to treat the metallic vapor plume inside the keyhole as a compressible fluid.

2.2. Self-consistent keyhole and weld pool dynamics

Accurate dynamic keyhole profiles and surface temperature distributions serve as the basis for modeling the metallic vapor dynamics during laser welding. Those physical characteristics could be determined by free surface heat transfer and fluid flow calculations of weld pool. In this paper, the thermofluid in weld pool is assumed as an incompressible fluid, since the density variation of material is small. The heat transfer and fluid flow of weld pool can be described by below equations, as follows:

$$\nabla \bullet \vec{U_l} = 0 \tag{1}$$

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

$$\rho_l C_p\left(\frac{\partial T_l}{\partial t} + (\vec{U_l} \bullet \nabla)T_l\right) = \nabla \bullet (k_l \nabla T_l) \tag{3}$$

where subscript l represents molten liquid in weld pool, $\vec{U_l}$, ρ_l, p_l, μ_l, $\vec{g}$, T_l, T_{ref}, β, C_p, k_l, K represent the three dimensional velocity vector, density, pressure, viscosity, gravitational vector, temperature of weld pool, reference temperature, thermal expansion coefficient, thermal capacity, thermal conductivity and the Carman–Kozeny coefficient, respectively.

In laser welding, severe topological variations of keyhole profiles could occur throughout the welding process. Here, the Level Set method is used to track the evolution of keyhole free surface. The movement equation of transient keyhole is expressed as follows [34]: