Optics and Lasers in Engineering 74 (2015) 47–58

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

3D transient multiphase model for keyhole, vapor plume, and weld pool dynamics in laser welding including the ambient pressure effect

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ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form
5 May 2015
Accepted 5 May 2015

Keywords:
Multiphase model
Keyhole dynamics
Weld pool dynamics
Vapor plume dynamics
Ambient pressure effect

ABSTRACT

The physical process of deep penetration laser welding involves complex, self-consistent multiphase keyhole, metallic vapor plume, and weld pool dynamics. Currently, efforts are still needed to understand these multiphase dynamics. In this paper, a novel 3D transient multiphase model capable of describing a self-consistent keyhole, metallic vapor plume in the keyhole, and weld pool dynamics in deep penetration fiber laser welding is proposed. Major physical factors of the welding process, such as recoil pressure, surface tension, Marangoni shear stress, Fresnel absorptions mechanisms, heat transfer, and fluid flow in weld pool, keyhole free surface evolutions and solid–liquid–vapor three phase transformations are coupling considered. The effect of ambient pressure in laser welding is rigorously treated using an improved recoil pressure model. The predicated weld bead dimensions, transient keyhole instability, weld pool dynamics, and vapor plume dynamics are compared with experimental and literature results, and good agreements are obtained. The predicted results are investigated by not considering the effects of the ambient pressure. It is found that by not considering the effects of ambient pressure, the average keyhole wall temperature is underestimated about 500 K; besides, the average speed of metallic vapor will be significantly overestimated. The ambient pressure is an essential physical factor for a comprehensive understanding the dynamics of deep penetration laser welding.

1. Introduction

Nowadays, deep penetration laser welding has been widely applied to aerospace, nuclear power, automotive, shipbuilding, and other important industries. In deep penetration laser welding, a slender vapor cavity, also called a keyhole which when filled with high temperature vapor plume or plasma, could be produced in an exothermic liquid weld pool due to the evaporation of the material. The transient keyhole, vapor plume, and weld pool dynamics are self-consistently correlated, and closely associated with the final quality of the laser weld joints. Mathematical modeling of the dynamics of the keyhole, vapor plume, and weld pool could be beneficial for the physical understanding and process optimization of deep penetration laser welding.

Many models have been proposed for understanding the physical process of deep penetration laser welding over the past 40 years. Earlier models [1–4] mainly considered the heat transfer behaviors of the welding process, which were often used to predict the keyhole geometries or weld profiles. Possible fluid flow behaviors of a weld pool induced by thermal-capillary effect and vapor plume frictions were also studied based on calculated or observed fixed keyhole profiles [5,6]. Their works have inspired researchers to study further the interactions between the keyhole, weld pool, and vapor plume in laser welding. However, these models mainly assumed that the keyhole has a quasi-steady profile, and cannot be used to simulate the evolution and oscillation of the keyhole from the beginning to a quasi-steady welding. Two-dimensional (2D) [7,8] or three-dimensional (3D) [9] free surface based models, capable of describing the transient, self-consistent keyhole, weld pool dynamics, and even the formation process of porosity defects, were proposed for laser welding during the past decade. This work makes it possible to predict the transient evolution of the self-consistent keyhole and weld pool. Nevertheless, the plume dynamics inside the transient keyhole, which has important effects on the transient keyhole and weld pool dynamics [10,11], cannot be predicted with these models. In recent years, several more prominent models were proposed to predict the self-consistent keyhole, weld pool, and vapor plume dynamics. The pioneering attempt was made by Ki et al. [12,13] from the University of Michigan for CO_2 laser welding. In their work the main physical phenomena involved in laser welding process have been considered. The keyhole free surface was tracked using the Level Set method. A Symmetrically Coupled

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http://dx.doi.org/10.1016/j.optlaseng.2015.05.003
0143-8166/

Gauss Seidel (SGGS) method was adopted to solve the model by using a powerful computer. Courtois et al. [14] have proposed a novel model based on Comsol Multiphysics software for keyhole, weld pool, and plume dynamics of Nd:YAG laser welding. In their model the energy transfer between the laser and keyhole interface was treated as a wave propagation problem by solving the Maxwell's equations, and the evaporation rate and the vaporization induced recoil pressure were included as localized source terms only at the keyhole interface. However, several important physical factors, such as Marangoni shear stress were neglected. Meanwhile, this model, as well as the models in [12–14] may achieve unphysical results near the interface since numerical smearing techniques are used to treat the discontinuous keyhole interface, according to Pang et al. [9]. Recently, Tan et al. [15] developed a multiphase model for keyhole, weld pool, and vapor plume dynamics for deep penetration Nd:YAG laser welding. The interactions between the molten pool, vapor plume, and assisting gas and its effects on the keyhole dynamics are investigated using their transient multiphase model. However, in their model the ambient pressure effect has not been taken into consideration.

Previous research has shown that the ambient pressure has significant effects on the penetration and defects in laser welding. For example, Katayama et al. [17] found that the state of the melt pool will become calmer when the ambient pressure decreases from atmospheric pressure to vacuum. Böerner et al. [18] demonstrated that the penetration depth will increase more than 110% in the low-speed laser welding process when the ambient pressure decreases from atmospheric pressure to vacuum. Amara et al. [6] showed that the ambient pressure has important effects on flow behaviors of the metallic vapor. The speed of the metallic vapor can increase to several thousand meters per second from less than 300 m/s, when the ambient pressure changes from 10 bar to 0.1 bar. Recently, Hirano et al. [19] found that the ambient pressure can reduce the evaporation rate when the temperature of evaporation surface is lower than or around the boiling point. The aforementioned research demonstrates that the ambient pressure may have great effects on the keyhole, weld pool, and metallic vapor dynamics in the laser welding process. Unfortunately, none of the previous comprehensive laser welding models [11–16] has considered this important physical factor.

In this paper, a novel 3D multiphase transient model rigorously incorporating the effects of ambient pressure is proposed and validated. The model can simultaneously simulate the evolution of the transient self-consistent keyhole, vapor plume, and weld pool in the deep penetration laser welding process. Major physical factors such as recoil pressure, surface tension, Marangoni shear stress, buoyancy force, multiple reflections Fresnel absorption, heat transfer, and fluid flow of weld pool, gas–solid–liquid multiphase transformations are included in the model. The predicted keyhole wall temperature and speed of metallic vapor using the models without the effect of ambient pressure are investigated by comparing with the corresponding results that include this effect. The proposed model is evaluated by comparing the simulation results with in-situ imaging experiments of laser welding process and literature results.

2. Mathematic modeling

Here the fiber laser welding (1.07 μm wavelength) is mainly considered, although the model developed here can easily be extended to other laser welding processes. To make the model tractable, we make several simplifications. The beam profile is assumed to be Gaussian. Besides, since there are theoretical difficulties in finding proper boundary conditions for compressible modeling of the vapor plume in the transient keyhole, the vapor

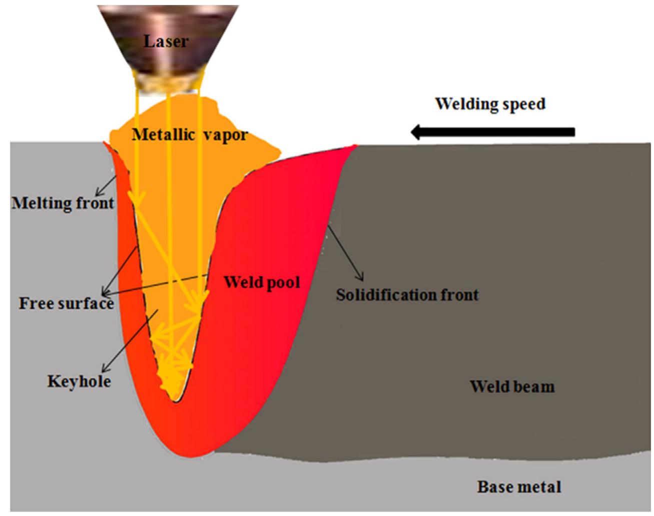

Fig. 1. Schematic of deep penetration laser welding.

plume is assumed to be an incompressible gas. Moreover, the possible friction effect of the vapor plume towards the keyhole is neglected in the model, following most of previous free surface models [12,14–16]. Fig. 1 shows the schematic of the deep penetration laser welding process. The major nomenclature used in this paper is given in Table 1. Other symbols in governing equations are defined when they are first introduced.

2.1. Governing equations

2.1.1. Transient keyhole and weld pool dynamics

In the welding process the dynamics of the self-consistent keyhole and weld pool can be solved by our previous sharp interface (SI) model of Pang et al. [9]. The heat transfer and flow behaviors of an incompressible molten liquid in a weld pool can be described in [9]

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

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

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

where C is an inertial coefficient related to the liquid fraction f_l, $C=0.13f_l^{-3/2}$ [9]. K is the Carman–Kozeny coefficient of mixture model. The time-dependent keyhole free surface, i.e., the vapor plume–weld pool interface is tracked by the Level Set method [20]

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

2.1.2. Vapor plume dynamics

Here, the vapor plume or plasma in the keyhole in deep penetration laser welding is mainly assumed to be influenced by recoil pressure, ambient pressure, and assisting gas. Previous experiments have demonstrated that in fiber laser welding the ionization degree of a high temperature vapor plume is very small [21], as a consequence the gaseous phase in the keyhole can be assumed to be completely full with metallic vapor plume. Based on above considerations, the dynamics of the vapor plume in the