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Numerical simulation of full penetration laser welding of thick steel plate with high power high brightness laser

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ABSTRACT

Full penetration laser welding was carried out on a 10 mm steel plate using a 16 kW maximum power continuous wave thin disk laser. Upper surface and lower surface of molten pool were observed synchronously with two high speed CCD cameras during the welding process. The lower surface was much longer and more unstable than the upper one. A three dimensional laser deep penetration welding model in which volume of fluid (VOF) method was combined with a ray-tracing algorithm was used to simulate the dynamic coupling between keyhole and molten pool in laser full penetration welding. The calculated weld cross-section morphology and molten pool length on both upper side and lower side agree well with experimental results. Evolution of molten pool in lower side during full penetration laser welding was analyzed, periodical features of energy coupling, molten pool behavior and keyhole dynamics in laser full penetration welding were identified and discussed.

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1. Introduction

In recent years, a new generation of high-power high-brightness solid state laser marked by fiber laser and thin disk laser has entered the market. Therefore, thick metal welding technology using high brightness solid state laser has obtained a great development potential overcoming some previous limitations. Kawahito et al. (2007) obtained a bead with a depth-to-width ratio of about 11 at 130 μm spot diameter, which can compete with the bead aspect ratio produced by electron beam welding. Zhang et al. (2011a) successfully carried out single pass full penetration welding of up to 50 mm thick metal plate using high brightness laser. However, laser full penetration welding of thick plate would have a higher demand in process control than laser partial penetration welding. Avilov et al. (2012) observed a complete drop through of the liquid metal during fiber laser welding of 20 mm thick $AlMg_3$ plate. Bachmann et al. (2012) pointed out that thermo capillary convection would be very strong on both upper and lower sides of the specimen during full penetration laser welding and the weld pool surfaces would become destabilized by the large convection velocities. Considering the increased plate thickness involved in laser welding, it becomes much more difficult to stably maintain a keyhole formed in laser full penetration welding process, and thus weld defects such as blowhole, porosity and hot crack become more likely to happen accordingly.

Experimental study of the coupling dynamics of molten pool and keyhole with satisfactory details is an extremely difficult mission. Fabbro (2010) experimentally studied the keyhole dynamics of full penetration welding process and found that different effects depending on the weld pool dynamics and plume interaction strongly disturbed the keyhole stability when the welding speed was reduced. It is a pity that only thin metallic sheet was considered in Fabbro's study. Kawahito et al. (2011) performed a X-ray transmission in situ observation in 10 kW fiber laser welding process. They found that with the increasing of welding speed the keyhole appeared to be expanded backward by strong ejection of laser-induced plume generated from the front wall. X-ray transmission in situ observation method is effective way of studying molten pool and keyhole behavior. However, the application of X-ray transmission in situ observation is limited because of the high cost and the possible harm from X-ray radiation. In order to improve the understanding of laser full penetration welding process, many research efforts have been devoted to numerical simulation. Ye and Chen (2002) carried out a 3D modeling of laser full penetration welding and found that Marangoni convection played critical role in determining the temperature distribution in the workpiece. Du et al. (2004) simulated full penetration laser beam welding of titanium alloy and found

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that melt flow driven by surface tension was responsible for the formation of "hourglass" cross-section profile. Rai et al. (2008) created a laser welding model taking into account the enhanced heat and mass transfer due to turbulence in the weld pool. They found that convective heat transfer was the main mechanism of heat transfer in the weld pool and affected the weld pool geometry and the solidification characteristics of welds. Zhang et al. (2011b) numerically found that the interaction between metallic vapour and molten melt could be well controlled by using the side gas flow during laser full-penetration welding. These researches improved our knowledge of full penetration laser welding. At the same time, it should be noted that dynamic effects of recoil pressure on molten pool during laser full penetration welding were neglected or underestimated in the numerical researches introduced above.

Recent years, some numerical models including free surface tracking or capturing technique have been successfully used to study the laser partial penetration welding process. Most noticeable are the VOF method-based laser welding model and the Level Set Method-based laser welding model. Up to now, VOF method-based laser welding model has already been employed to study the temperature field (Wu et al., 2009), keyhole dynamics (Zhao et al., 2011), melt pool movements (Amara and Fabbro, 2008), porosity formation (Zhao and DebRoy, 2003), humps formation (Amara and Fabbro, 2010) and transport phenomena (Zhou et al., 2006) during laser welding process. Otto et al. (2011) simulated the laser full penetration welding of 1 mm stainless steel by using VOF method. They found that the waves running down the keyhole front was the reason for keyhole oscillations. They also reported that in the simulations with high welding speed the formation of pores in the weld seam can be observed. Most recently, Tan et al. (2013) created a three-dimensional transient model employing the sharp interface method. They found that the interplay of the multiple reflections and the plume attenuation played important roles in partial penetration laser welding.

A series of progress in three-dimensional transient modeling on laser deep welding based on VOF method was made by Na's group. Cho and Na (2006) established a three-dimensional laser welding model in which VOF method was combined with a ray-tracing algorithm to calculate laser energy deposition on keyhole wall. Furthermore, Cho and Na (2009) extended their model from laser welding simulation to laser-arc hybrid welding simulation. Recently, Cho et al. (2012) improved the ray-tracing algorithm in their model.

Although better understanding of the underlying scientific principles of laser deep penetration welding have already be obtained based on these numerical studies, there remains plenty of unexplored topics. For example, numerical studies of full penetration laser welding of thick plates which is most widely used in industry field are really limited. In present study, the VOF-based laser deep welding model developed by Na's group is extended from partial penetration laser welding to full penetration laser welding of thick plate. The general features of laser full penetration welding process are simulated and analyzed.

2. Mathematical model

2.1. Assumptions

Assumptions employed in simulation are listed below:

(1) The molten metal is assumed to be laminar, incompressible and Newtonian fluid.
(2) Power density of laser beam is assumed to be with a Gaussian distribution.
(3) Evaporation induced recoil pressure was decided by Clausius–Clapeyron equation.
(4) Inside the blind keyhole, the vapor velocity is assumed to increase linearly along the depth from zero velocity at the bottom of the keyhole to its calculated velocity at the entrance of the keyhole.
(5) Inside the upper half of through keyhole, the vapor flows upward and the vapor velocity is assumed to increase linearly from zero velocity at half thickness of the plate to its calculated velocity at the upper entrance. Inside the lower half of through keyhole, the vapor flows downward and the vapor velocity is assumed to increase linearly from zero velocity at half thickness of the plate to its calculated velocity at the lower entrance.
(6) Radiation heat transfer from plasma/metallic vapor to workpiece is considered at both upper and lower surface of workpiece.
(7) The buoyancy force is modeled with the Boussinesq approximation.

2.2. Governing equations and laser welding model

The governing equations describing the melt flow and heat transfer in the molten pool and the theory of VOF method can be easily found in literatures (Flow Science, 2008), so they are not repeated here. A detailed introduction of the laser beam profile, sub-model of multiple reflections in keyhole, sub-model of Fresnel absorption, sub-model of recoil pressure, the calculation method of vapor velocity, the calculation method of shear stress and the calculation method of the impact of the vapor on opposite keyhole walls can be found in the previously published papers of Na's group (Cho and Na, 2006; Cho et al., 2010, 2012).

2.3. Material properties and boundary conditions

Low carbon steel plate with a thickness of 10 mm was considered in this study. The physical properties of the material and coefficients used in the simulation are shown in Table 1. Fig. 1 shows the coordinate system and computational domain used in the study. The analytic domain was set as 56 mm in length, 26 mm in width, and 20 mm in height including the void regions at both top and bottom side for free surface tracking. Totally, 871,396 cells have been used in the computation, and the size of the minimum cell is 0.2 mm × 0.2 mm × 0.2 mm, as shown in Fig. 2.

The governing equations are solved using the computational fluid dynamics code FLOW3D. The energy on both top and bottom free surface is balanced between the laser heat flux, the heat

Table 1
Material properties used in simulation.

Physical properties	Value
Density of liquid metal ρ (kg m^{-3})	6900
Density of solid metal ρ (kg m^{-3})	7800
Thermal conductivity of liquid k_L (W m^{-1} K^{-1})	26.9
Thermal conductivity of solid k_S (W m^{-1} K^{-1})	32.3
Viscosity μ (kg m^{-1} s^{-1})	0.0059
Surface tension γ (N m^{-1})	1.87
Surface tension gradient $d\gamma/dT$ (N m^{-1} K^{-1})	-4.3×10^{-4}
Specific heat of solid C_S (J kg^{-1} K^{-1})	726
Specific heat of liquid C_L (J kg^{-1} K^{-1})	732
Latent heat of fusion h_{SL} (J kg^{-1})	2.77×10^5
Latent heat of vaporization h_V (J kg^{-1})	7.34×10^6
Coefficient of thermal expansion β	1×10^{-5}
Liquidus temperature T_L (K)	1798
Solidus temperature T_S (K)	1768
Boiling temperature T_V (K)	2900
Convection heat transfer coefficient h (W m^2 K^{-1})	10
Emissivity ε	0.4

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