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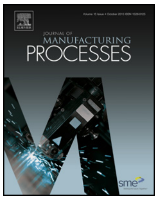

Technical Paper

Numerical simulation of keyhole behaviors and fluid dynamics in laser–gas metal arc hybrid welding of ferrite stainless steel plates

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ABSTRACT

The fluid dynamics in weld pool and keyhole behaviors in laser–gas metal arc hybrid welding play a dominant role in affecting the weld quality of ferrite stainless steel plates. In this study, a transient model is developed for numerical simulation of the keyhole dynamics and heat transfer & fluid flow in hybrid weld pool. The heat, mass and momentum transfer due to droplets as well as the interaction between laser and arc are taken into account. The formation, expansion and sustainment of keyhole in weld pool are numerically simulated, and the transient variation of keyhole is demonstrated in three stages. The weld pool and keyhole shapes and sizes, and the fluid flow and thermal field in hybrid weld pool are quantitatively analyzed. The model is validated by hybrid welding experiments on ferrite stainless steel plates. It lays foundation for optimizing the process parameters in hybrid welding.

1. Introduction

Nowadays ferrite stainless steel is widely used in manufacturing railway wagons [1] since it is a low cost stainless steel with good corrosion resistance. During welding process, the thermal cycles experienced causes the grain growth in the heat-affected zone (HAZ), which results in the deterioration of the impact toughness at a low temperature and intergranular corrosion resistance property [2]. Thus, the heat transfer process and temperature history has to be controlled carefully in welding ferrite stainless steel to reduce the HAZ width and grain size in the HAZ [3,4]. Conventional gas metal arc welding (GMAW) has shortcomings of lower welding speed, less weld penetration and wider HAZ width [5]. Though laser beam welding offers deep weld penetration with high welding speed and small HAZ width, it requires stringent parts positioning with lower gap bridging ability, and its high welding speed leads to high solidification rates which may in turn lead to cracking and/or pores in the seam [6]. To enhance capability of two processes and compensate deficiencies of each individual, laser–GMAW hybrid welding process has been developed [7–9]. Compared with single laser welding and single GMAW, laser–GMAW hybrid welding shows great advantages in both welding efficiency and weld quality. Through synergy effect, the hybrid welding can realize the process performance of “1 + 1 > 2”, and produces narrower HAZ. Thus, laser–GMAW hybrid welding has significant potential to solve the challenge problems in welding ferrite stainless steel structures [10,11].

However, the number of process parameters in laser–GMAW hybrid welding is increased because it involves not only the parameters of individual process, but also the new parameters resulting from the combination of two processes, such as the relative position and posture between the laser head and GMAW torch [5,12]. Though the increased number of process parameters allows a flexible adjustment of the hybrid welding process, it brings complicated underlying mechanisms and places higher demands on the process optimization [13]. Till to now, most of the relevant welding parameters are determined empirically, which requires a substantial level of practical experiences. Though extensive experimental investigations and some theoretical studies have been conducted in hybrid welding, there is still a lack of fundamental investigations involving mathematical modeling and understanding of hybrid welding process [13–15]. Some researchers [5,13] developed a combined volumetric heat source model to conduct the thermal analysis of hybrid welding and predict the shape and size of hybrid welds, but only thermal conduction phenomena was taken into account. It is well recognized that fluid flow in weld pool affects the heat transfer and the temperature distribution in welded base metal, in consequence having significant influence on the keyhole dynamics and weld pool behaviors [16,17]. Therefore, it is essential to develop a thermo-fluid model for analyzing the welding thermo-phenomena to get deep insight into the process mechanisms and elucidate the relationship between the thermal history and the microstructure

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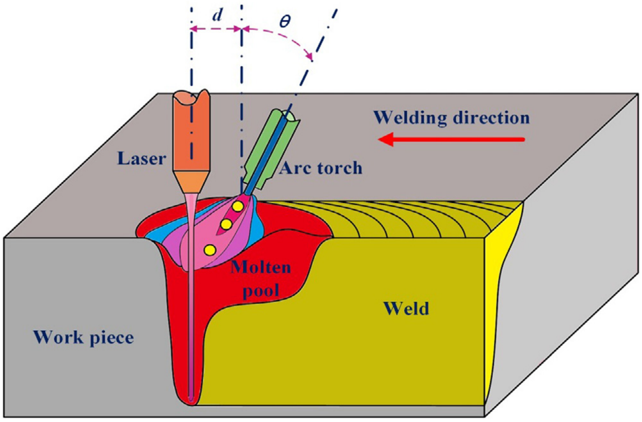

Fig. 1. Schematic of laser–gas metal arc hybrid welding.

& properties of weld joints. Cho and Na [18] developed a transient three-dimensional model to simulate the interaction between droplets and weld pool, the dynamic keyhole evolution, bubble formation and the flow patterns of the molten pool in hybrid laser–GMA welding. Zhang and Wu [19] developed a three dimensional quasi–steady state model of coupled fluid flow and heat transfer for laser–GMAW hybrid welding of ferrite stainless steel, and analyzed the effect of fluid flow in the weld pool on the temperature field and weld formation. However, it did not include the important process of droplet transfer related to GMAW and used a preset keyhole profile in weld pool. Thus, it cannot deal with the formation of the weld reinforcement.

In this study, a model for analyzing thermo-physical phenomena and fluid dynamics in laser–GMAW hybrid welding is developed through considering the laser–gas metal arc interaction and the effects of heat, mass and momentum transfer from droplets on the keyhole dynamics and weld pool behaviors. The transient evolution of fluid flow and temperature field in hybrid weld pool with a dynamic keyhole is quantitatively analyzed. The calculated results are validated by hybrid welding experiments on ferrite stainless steel plates. It lays foundation for optimizing the process parameters in hybrid welding.

2. Mathematical modeling

As shown in Fig. 1, the laser beam is leading, while the gas metal arc is trailing. The relative angle between them is represented by θ, and the laser–wire distance is denoted by d. The heat from the laser beam, the gas metal arc and the droplets is deposited into a single weld pool, and the recoil pressure due to metal vapor causes a keyhole formation inside the weld pool. For modeling the heat transfer and fluid flow in weld pool with a dynamic keyhole during hybrid welding, some simplified assumptions have to be made as follows:

(1) The molten metal in weld pool is laminar, incompressible and Newtonian fluid.
(2) The physical properties of ferrite stainless steel are constants.
(3) The loss of molten metal due to evaporation is neglected.

As schematically shown in Fig. 2, half of the workpiece was taken as the calculation domain due to the symmetry with respect to the joint line. During hybrid welding, both keyhole and weld pool boundaries need to be tracked, and the volume of fluid method was used to determine the interface between air/vapor and liquid metal. Thereby, the geometric domain consists of air phase layer and metal workpiece. The hybrid heat source (laser beam plus gas metal arc) travels along the welding direction (positive x-axis) with welding speed v_0.

2.1. Governing equations

With the above-mentioned assumptions, the governing equations can be expressed in Cartesian coordinates as follows:

Mass conservation equation

$$\rho\frac{\partial u_i}{\partial x_i}=S \tag{1}$$

where ρ is density, $u_i(i=1,2,3)$ is the velocity components in x, y, z directions, and S is the mass source term from transferring droplets.

Momentum conservation equation

$$\rho\frac{\partial u_j}{\partial t}+\rho\frac{\partial(u_iu_j)}{\partial x_i}=-\frac{\partial P}{\partial x_j}+\frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_i}{\partial x_j}\right)-C\frac{(1-f_L)^2}{f_L^3+A}u_j+\rho g_i\beta_0\Delta T+P_A+P_R+P_D+S_j \tag{2}$$

where P is pressure, i or j takes values of (1,2,3) representing (x,y,z) axis, μ is viscosity, C is Carman–Kozeny coefficient, f_L is the liquid fraction, A is a small constant, g_i is gravitational acceleration, β_0 is thermal expansion coefficient, ΔT is the temperature difference, P_A is arc pressure, P_R is recoil pressure, P_D is impact of droplets, and S_j is electromagnetic force terms. The liquid fraction is assumed to be a linear function of the temperature:

$$f_L=\begin{cases}0 & T\le T_S\\ \dfrac{T-T_S}{T_S-T_L} & T_S<T<T_L\\ 1 & T\ge T_L\end{cases} \tag{3}$$

where T is temperature, and T_S and T_L are solidus and liquidus temperature, respectively. The electromagnetic force term S_j may be referred to literature [19].

Energy conservation equation

$$\frac{\partial h}{\partial t}+\rho\frac{\partial(u_ih)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\lambda}{c_P}\frac{\partial h}{\partial x_i}\right)+q_s \tag{4}$$

$$h=c_pT+f_LL_f \tag{5}$$

$$q_s=q_L+q_A+q_D \tag{6}$$

where h is enthalpy, c_P is specific heat, λ is thermal conductivity, q_s is source term, q_L is laser heat, q_A is arc heat, q_D is enthalpy of droplets, and L_f is latent of fusion.

VOF (volume of fluid) equation

$$\frac{\partial F}{\partial t}+\nabla\cdot(\vec{v}F)=0 \tag{7}$$

where F is the volume of fluid in a cell, and $\vec{v}$ is the fluid velocity vector. A cell with $F=1$ is full of fluid, whereas a zero value of F corresponds to a cell that contains no fluid. A cell with a F value between 0 and 1 contains a free surface (keyhole wall).

2.2. Definite conditions

When hybrid welding starts, both the gas metal arc and laser beam deposit thermal energy on the workpiece. The initial condition ($t=0$) is as follows:

$$T_0=298\text{K} \tag{8-1}$$

$$u_i=0,\quad (i=1,2,3) \tag{8-2}$$

where T_0 is the initial temperature.