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Research Paper

A 3-D lattice Boltzmann analysis of weld pool dynamic behaviors in plasma arc welding

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HIGHLIGHTS

- Develop a 3-D LB model to analyze the heat and mass transfer in moving PAW.
- Compared with FVM, computational efficiency is improved by program parallelism.
- Introduce an included angle to analyze coupled heat transfer and fluid flow.
- The collision of circulations contributes to the formation of hump on fusion line.

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ABSTRACT

In this paper, a three-dimensional lattice Boltzmann model is first applied to describe the melting pool evolution in moving plasma arc welding. The heating and key-holing effects of the arc are taken into account by a combined volumetric heat source model. The calculation efficiency is greatly improved by parallel computation. The predicted weld pool geometries with obvious hump agree well with the experimental data, whether for complete joint penetration or not. Several circulations are revealed which colliding with each other at the middle of the fusion lines, and it results in the included angle between the velocity vector and temperature gradient smaller than 90°, along with a quite small velocity. This is considered to contribute to the formation of hump in the fusion line. Finally, a discussion is made on the operational parameters including plasma arc power and welding speed, and we give the optimal prediction based on some different condition simulations. Our study is expected to perform more inherent simulation with LB method and provide appropriate operating parameters to benefit the practical welding production.

1. Introduction

Plasma arc welding (PAW), as one of the most highly efficient welding technologies, has been widely used in industrial production, such as structural steel [1], airplane [2], space ship [3] and other important products of welding manufacturing due to its key-holing effect [4]. And numerical simulations associated with its processes become a hot spot. Researchers establish models with modern computer in order to help understand the mechanism of penetration and the dynamic evolution of the keyhole, and analyze the heat transfer in the weld pool.

Due to the importance of key-holing effect in PAW process, researchers usually assume certain keyhole shapes [5] and consider the interaction between the plasma arc and the weld pool, or employ the Volume of Fluid (VOF) technique and some other interface tracking methods to track the dynamic-variation keyhole boundary [6–8]. Although it is more intuitive and sounds to consider the dynamic change of the keyhole during the welding process, the calculation is time-consuming and it is difficult to accurately predict the weld pool geometries. Therefore, it is advisable to consider the key-holing effect by establishing a heat source model, leaving out tracking the keyhole boundaries [9–11]. Apparently, this approach restricts the computation domain inside the workpiece, simplifying the programming process and improving computational efficiency. With mountains of work, such as the Gaussian heat source, the conical heat source model [9] or the double-ellipsoid and the cylindrical combination heat source model [10], the simulating performance of heat source model gradually improved.

It should be pointed out that most previous studies are based on the

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Nomenclature

a_1, a_2, b, c	shape coefficients of heat source
r_e, r_i	radius of cone ends
C_p	specific heat
f_l, f_s	liquid fraction and solid fraction
L_α	latent heat of material
R	ideal gas constant
g	acceleration of gravity
D_0	mushy zone constant
Q_0	thermal energy absorbed from plasma arc
Z_e, Z_i	Z-coordinate of cone ends
$\boldsymbol{V_0}$	moving speed of welding torch
f_i	density distribution in direction i
F_i	sum of force terms in direction i
h_i	temperature distribution in direction i
Q_i	heat source in direction i
$\boldsymbol{e}_i$	discrete lattice velocity in direction i
c_s	lattice sound speed
$\boldsymbol{a}$	external force density
q	internal heat source
k_T	thermal conductivity
H	total enthalpy
H_l, H_s	enthalpy of liquidus, solidus point
T	temperature
T_m	melting temperature of material
T_∞	ambient temperature
T_l, T_s	liquidus and solidus temperature
h	convective heat transfer coefficient
I	current
U	welding voltage
x, y, z	coordinates
x_0, y_0, z_0	initial position of heat source

Greek symbols

μ_m	magnetic permeability of material
σ	Stefan-Boltzmann constant
σ_j	current distribution parameter
β_T	thermal expansion coefficient
ε	radiation emissivity
ρ	density
μ	dynamic viscosity
ν	kinetic viscosity
χ_1, χ_2	energy distribution coefficient
η	welding efficiency coefficient
ω_i	weighting coefficient

Superscripts and subscripts

eq	equilibrium distribution function
i	directions in a lattice

traditional Computational Fluid Dynamics (CFD) method with continuous fluid hypothesis, and it is difficult to explain the micro-characteristics of the physical system [12]. In recent years, the lattice Boltzmann method (LBM) has become the most popular mesoscopic simulation method, which enjoys advantages of both macroscopic and microscopic approaches. LBM has been proved effective for irregular computational boundaries, especially for multi-phase and multi-component flows [13–16]. Furthermore, the algorithm simplicity and intrinsic data locality makes the LB method favorable for massively parallel programming [16–18], which is required for large-scale engineering applications. In addition, utilizing graphics processing unit (GPU) as computational accelerators has attracted great attention in recent years due to its combined tremendous computing power and superior memory band width [19,20]. Generally, there are three major LBM approaches to simulate the solid–liquid phase change problems: (1) the phase-field based method [21,22], (2) the enthalpy-based method [23–25], and (3) the immersed boundary method [26]. Among these three schemes, the enthalpy-based method is employed in our simulation. The calculation procedure is simplified by modifying the equilibrium distribution function for the temperature, and the phase interface is traced by updating the total enthalpy.

Basing on a series of experiments and data from previous research, our group proposed a combined effective heat source model to consider the key-holing effect [11]. Afterwards, VOF technology was employed to track the interface of the keyhole, and a dynamic heat source model was established relating to the dynamic keyhole growth [27]. Recently, we further used Finite Volume Method (FVM) to develop a unified model coupling plasma arc and weld pool [28]. However, these research lacked analysis of the fluid flow in the weld pool, whose effect on heat transfer was proven to be non-negligible [29]. To better understand the inherent weld formation mechanism of PAW, our group firstly developed a 2-D LB model to describe coupled fluid flow and heat transfer in the weld pool [29]. Although this study was limited to simulate spot (stationary) PAW process, it had obtained valuable results with more intuitive display and analysis of fluid flow than FVM method.

In this paper, LBM was further developed to study the moving PAW process and analyze the evolution of weld pool. The moving welding includes a dwell (static-torch) stage and then a torch-moving stage. During the dwell stage, the plasma arc rapidly heats and melts the workpiece, until there is complete joint penetration. Afterwards, as the torch continuously moves, the pool shape further changes, possibly expanding, or it may shrink. To numerically study the transport phenomena in the molten pool for the moving welding, 3-D model has to be developed rather than 2-D model. Compared with our previous 2-D simulation, program codes were modified for parallel computation and the relaxation time of the collision step was adjusted, in order to improve the efficiency and stability of the calculation. The volumetric heat source model was composed of an asymmetric double-ellipsoidal and a symmetric conical heat source, and the heat source keeps moving. The combined convection and radiation heat transfer boundary conditions (B.C.) were considered for the workpiece rather than the adiabatic B.C. assumed in 2-D simulation. We have particularly analyzed the effect of fluid flow in the molten pool on heat transfer, especially on the fusion line. Finally, considering the energy consumption and welding quality comprehensively, we gave the optimal process parameters among the working conditions of this paper. Our study is expected to improve the simulation by LB method and supply appropriate operating parameters to benefit the practical welding production.

2. Mathematical model

2.1. Governing differential equations

During a typical keyhole PAW process, the high-temperature plasma arc impinges on workpieces, releases a lot of heat and creates a molten pool. Afterwards, with the movement of the welding torch, the rear of the weld pool gradually cools and solidifies to form a weld. This process is schematically presented in Fig. 1.The three-dimensional mathematical model is developed by introducing the following assumptions.

(1) The top surface of the weld pool is flat, neglecting the effect of plasma arc pressure.
(2) A combined effective heat source model is used to consider the key-holing effect.