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Simulation of dendrite growth in the laser welding pool of aluminum alloy 2024 under transient conditions

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ABSTRACT

A macroscopic heat transfer and fluid flow model is developed to calculate the temperature and velocity fields in the laser welding pool of aluminum alloy 2024. The equations of temperature gradient and solidification rate are developed to consider the transient conditions during the laser welding process. The dendrite growth and solute concentration along the fusion boundary are predicted via the phase-field model under the transient conditions. The comparison of the simulation results with the measurements is carried out. Fusion profiles obtained by using a rotary-Gauss body heat source model are consistent with measurements. The computed dendrite morphology and primary dendrite arm spacing give a good agreement with experimental findings.

1. Introduction

Laser beam welding has many advantages including high energy density, high welding velocity, high flexibility, high productive efficiency, narrow welding width and deep penetration, compared with traditional arc welding. The performance of the laser welds is affected directly by the solidification process and resulting microstructures. It is of significance to investigate and predict the solidification process during the laser welding process. It is almost impossible to observe and investigate directly the solidification process by traditional experimental methods because of the complex characteristics of laser welding. Fortunately, the numerical techniques can reproduce this process with the development of computational materials science.

Prediction of the formation of solidification microstructures during the laser welding process is an important and supporting factor for technology optimization. Different kinds of numerical methods have been applied to simulate the solidification process during welding, especially the cellular automaton and phase-field model. Pavlyk and Dilthey (2004) predicted the dendritic morphology during the directional solidification of gas tungsten arc welding pool using cellular automata and phase field methods. Wei et al. (2007) applied cellular automaton algorithms to simulate the dendrite growth and solute diffusion along the fusion boundary in the welding pool. Zhan et al. (2008) simulated dendritic growth in tungsten inert gas welding molten pool of nickel-based alloys by using the CA-FD (Cellular Automaton – Finite Difference) model. Farzadi et al. (2008) predicted solidification microstructures at different locations along the fusion line during gas tungsten arc welding of Al-3 wt% Cu alloys using a phase-field model. Montiel et al. (2012) used the phase-field model to simulate microstructures in the solidification process of AZ31 magnesium alloys under the given welding conditions. Zheng et al. (2014) investigated the dendrite growth along the fusion boundary in the gas tungsten arc welding pool of 2A14 alloys using a quantitative phase-field model. The solidification process of the arc welding molten pool is simulated and predicted in detail. The dynamic solidification process of the laser welding pool is more complicated than that of the conventional arc welding. It is of difficulty to simulate and predict the solidification microstructures in the laser welding pool. Few works have paid attention to predicting dendritic growth and solute distributions in the laser welding molten pool. Tan et al. (2011) proposed a novel model coupled cellular automata and phase field methods to predict dendritic growth in the laser welding pool of aluminum alloy AA2024 under steady-state conditions. Tian et al. (2016) developed a three-dimensional CA-FE (Cellular Automaton-Finite Element) solidification model to simulate the microstructural evolution during laser deposition shaping of TC4 alloys neglecting the effects of flow field.

The solidification of the welding pool is nonlinear process. The steady-state conditions used in the above studies cannot realistically describe actual solidification process of the laser welding pool.

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The dendrite morphology and solute diffusion depend strongly on transient history and melt flow in the welding pool. A macroscopic heat transfer and fluid flow model is developed to predict the welding temperature and velocity fields in the laser welding pool of aluminum alloy 2024. The equations of temperature gradient and solidification rate are developed to consider the transient conditions of the laser welding pool. The transient conditions are closer to actual solidification process than the steady-state conditions in the laser welding pool. The dendrite growth and solute concentration along the fusion boundary are predicted by using a phase-field model under the transient conditions. The comparison of the computed results with the measurements is carried out to show reproducibility of computed results.

2. Description of the model

2.1. Macroscopic heat transfer and fluid flow model

The heat transfer process is calculated by using a three-dimensional model with the consideration of flow field. It is assumed that the liquid in the welding pool is Newtonian, incompressible and laminar and the solid is not flowing. The fluctuation on the top surface of welding pool is ignored. Marangoni effects caused by the surface tension and buoyancy body forces are considered to calculate the flow field in the welding pool. In order to calculate velocity and temperature fields in the welding pool, the equations of energy, mass and momentum conservation are defined as (Patankar, 1980)

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u_i) = 0 \quad (1)$$

Momentum conservation:

$$\frac{\partial(\rho u_i)}{\partial t} + \nabla\left(\rho u_i u_j\right) = \nabla(\mu \nabla u_i) + \frac{\mu}{K}(u_i - v) + S_{ui} \quad (2)$$

Energy conservation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla(\rho u_i h) = \nabla\left(\frac{k}{c_p}\nabla h\right) + S_h \quad (3)$$

where ρ is density, u_i and u_j is the velocity along the i and j directions, k is the thermal conductivity, v is the welding velocity, c_p is the specific heat, h is the enthalpy, μ is the viscosity, K is the Karman–Kozeny turbulent coefficient, S_{ui} is the source term of the momentum equation, S_h is the source term of the energy equation.

The source term of the momentum equation is affected by the porous media and the buoyancy in the solid-liquid mixing region. The source term of the momentum equation in x and y directions is defined as

$$S_{ui} = -\nabla p - C\left[\frac{(1-f_1)^2}{{f_1}^3 + B}\right] u_i \quad (4)$$

where p is the pressure, f_1 is the liquid fraction, B is a very small positive number introduced to avoid division by zero, C is an empirical constant.

In the z direction, the effects of the buoyancy on the source term are considered. The source term of the momentum equation is given by

$$S_{ui} = -\frac{\partial p}{\partial z} - C\left[\frac{(1-f_1)^2}{{f_1}^3 + B}\right] u_i + \rho\beta g(T - T_s) \quad (5)$$

where β is the thermal expansion coefficient, g is the gravitational acceleration, T_s is the solidus temperature. Effects of latent heat and external heat source on the heat transfer are considered, the source term of the energy equation is defined as

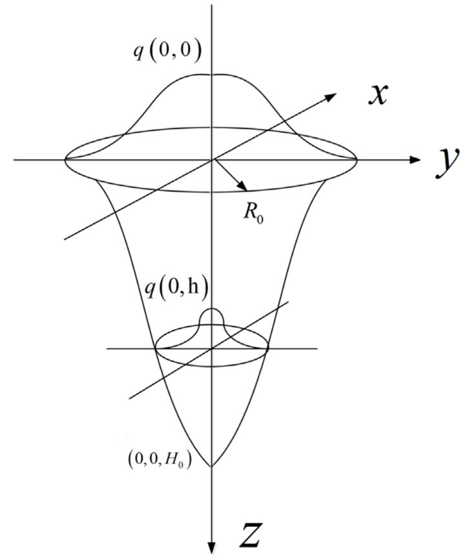

Fig. 1. Laser heat sorce model (Wu et al., 2004).

$$S_h = -\frac{\partial(\rho \Delta H)}{\partial t} - \nabla(\rho u_i \Delta H) + q(x, y, z) \quad (6)$$

where H is the latent heat, $q(x, y, z)$ is the heat flux density at the point (x, y, z).

As shown in Fig. 1, the rotary-Gauss body heat source model is applied to characterize the laser heat source (Wu et al., 2004). The cross section in z direction is regarded as a circle. The heat flux density obeys the Gaussian distribution in the cross section, and it reaches a maximum $q(0, z)$at the center of the circle. The heat flux density along the z direction $q(0, z)$ is a constant. The heat source model is defined as (Wu et al., 2004)

$$q(x, y, z) = \frac{9Q}{\pi R_0^2 H_0\left(1 - e^{-3}\right)} \exp\left[\frac{-9}{\ln\left(\frac{H_0}{z}\right) R_0^2}\left(x^2 + y^2\right)\right] \quad (7)$$

where Q is the effective laser energy, R_0 is the effective radius, H_0 is the height of heat source.

Effects of convective heat transfer and radiation heat transfer on the thermal transfer process are considered on the top surface. The equation of convective heat transfer and radiation heat transfer is defined as

$$-kGradT = -q(x, y, z) + h_c(T - T_0) + k_b\varepsilon\left(T^4 - T_0^4\right) \quad (8)$$

where $h_c(T - T_0)$ is the term of convective heat transfer, h_c is convective heat transfer coefficient, T_0 is ambient temperature, $k_b\varepsilon\left(T^4 - T_0^4\right)$ is the term of radiation heat transfer, ε is the heat exchanger effectiveness, k_b is the Boltzmanns constant. The equation of convective heat transfer and radiation heat transfer on the side and bottom surfaces is given by

$$-kGradT = h_c(T - T_0) + k_b\varepsilon\left(T^4 - T_0^4\right) \quad (9)$$

The boundary condition of the velocity field is given by

$$-\mu\frac{\partial u_1}{\partial z} = \frac{\partial \sigma}{\partial T}\frac{\partial T}{\partial x}, \quad -\mu\frac{\partial u_2}{\partial z} = \frac{\partial \sigma}{\partial T}\frac{\partial T}{\partial y}, \quad u_3 = 0 \quad (10)$$