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ScienceDirect
Trans. Nonferrous Met. Soc. China 27(2017) 1319−1326
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Numerical analysis of thermal fluid transport behavior during electron beam welding of 2219 aluminum alloy plate

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Received 26 March 2016; accepted 25 August 2016

Abstract: A two-dimensional mathematical model based on volume-of-fluid method is proposed to investigate the heat transfer, fluid flow and keyhole dynamics during electron beam welding (EBW) on 20 mm-thick 2219 aluminum alloy plate. In the model, an adaptive heat source model tracking keyhole depth is employed to simulate the heating process of electron beam. Heat and mass transport of different vortexes induced by surface tension, thermo-capillary force, recoil pressure, hydrostatic pressure and thermal buoyancy is coupled with keyhole evolution. A series of physical phenomena involving keyhole drilling, collapse, reopening, quasi-stability, backfilling and the coupled thermal field are analyzed systematically. The results indicate that the decreased heat flux of beam in depth can decelerate the keyholing velocity of recoil pressure and promote the quasi-steady state. Before and close to this state, the keyhole collapses and complicates the fluid transport of vortexes. Finally, all simulation results are validated against experiments.

Key words: heat transfer; fluid flow; keyhole dynamics; electron beam welding; mass transport; vortex; recoil pressure; backfilling

1 Introduction

When a high-power density electron beam irradiates on the substrate surface, accompanying with strong metal evaporation, a pinhole surrounded by liquid molten metal emerges, which is called as “keyhole”. Its existence substantially changes the physical transport mechanism of welding pool, differentiating it from the traditional fusion welding methods [1]. It has been reported that the keyhole, which is not smooth and dynamic fluctuating [2,3], remarkably influences the welding quality and defect formation, such as undercut, humping, porosity, and spiking [4−6].

So far, the extensive research works have been done to study the keyhole dynamics and welding pool’s transport phenomena. These works can be summarily divided into two aspects, one based on experimental observation and the other based on numerical calculation. On experimental aspect, X-ray camera, secondary emitted beams, photodiodes and CCD camera technologies have been utilized to observe the formation and fluctuation of keyhole [2,3,7−9]. However, building such observation systems is expensive and time-consuming. Numerical calculation seems a more promising and desirable tool. On numerical calculation aspect, the VOF or Level Set tracking algorithm, and fluid driving forces combining with ray tracing techniques have been widely adopted to investigate the heat transfer, fluid flow and keyhole dynamics. For example, the formation, backfilling and collapse of keyhole, hydrodynamics of vapor plume, multiple reflections and the coupled heat and mass transports in laser beam welding (LBW) and plasma arc welding (PAW) fields have been researched in depth [10−15]. However, these findings cannot be utilized to reveal the EBW’s transport mechanism since their different working pressures [16].

So far, in EBW numerical studies, most of works have mainly concentrated on analyzing the thermal effect and related thermal stress issues [17−19], and thus it is not necessary to trace the detailed keyhole evolution and fluid flow. On the other hand, in order to better predict the weld formation and welding defects, detailed keyhole evolution information is indispensable. However, such kind of researches in EBW field is very limited. RAI et al [16] developed a three-dimensional numerical model to analyze the heat transfer, fluid flow and wall temperature variations on keyhole wall in EBW process at different power density distributions. However, they

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DOI: 10.1016/S1003-6326(17)60153-5

ignored the keyhole evolution and its effects on thermal-fluid transport of welding pool. TOMASHCHUK et al [20] utilized a two-dimensional numerical model to simulate the morphology and velocity field distribution in copper–stainless steel dissimilar electron beam welds. However, the keyhole evolution and weld surface deformation are also not considered.

In this work, a 2D mathematical model is proposed to study the thermal-fluid transport phenomena in 2219 aluminum alloy EBW pool. In the model, an adaptive heat source model which can trace the keyhole evolution is employed to simulate the heating process of electron beam. The driving forces of liquid metal in welding pool and heat source model are all implemented by UDF (user-defined function). Based on this model, a series of fluid transport phenomena involving the drilling, collapse, reopening and backfilling of keyhole coupling with heat transfer are analyzed. Finally, all the simulation results are validated against experimental results.

2 Mathematical model

In this work, a 2D computational domain is created (as shown in Fig. 1) and discretized by the finite volume method based on ANSYS Fluent software. And VOF multiphase model is adopted to trace the welding pool's free surface deformation. The whole domain consists of vapor phase, liquid phase (i.e., welding pool), mushy zone and solid phase (i.e., substrate, which is considered as a kind of liquid phase with a very large viscosity). The following assumptions are made in this simulation.

1) Liquid metal of welding pool and gas phase are assumed to be laminar, incompressible and Newtonian fluid.

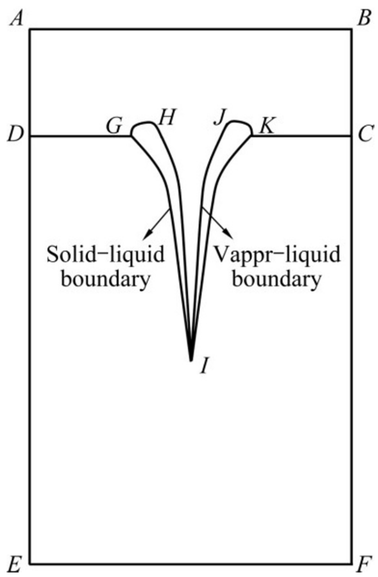

Fig. 1 Schematic sketch of 2D computational domain of EBW process

2) All material properties are temperature-dependent except density.

3) Thermal buoyancy obeys Boussinesq approximation.

4) Plasma formation and multiple reflections inside keyhole are not considered.

2.1 Governing equations

Based on the above assumptions, the conservation equations of mass, momentum and energy are written as

Mass conservation equation:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{1}$$

Momentum equation:

$$\rho\left(\frac{\partial \boldsymbol{U}}{\partial t} + \nabla\cdot(\boldsymbol{UU})\right) = \nabla\cdot(\mu\nabla\boldsymbol{U}) - \nabla p + \frac{(1-f)^2}{(f^3+\delta)}A_{\text{mush}}\boldsymbol{U} + P_\sigma + P_{\text{r}} + \rho g\beta(T - T_{\text{ref}}) \tag{2}$$

Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla\cdot(\rho\boldsymbol{U}H) = \nabla\cdot\left(\frac{k_1}{c_p}\nabla T\right) + q_{\text{ebw}} \tag{3}$$

where $\boldsymbol{U}$ is the velocity vector; p is the pressure, μ is viscosity, ρ is material density, and the third term on the right denotes the momentum sink employed by enthalpy-porosity technique to consider solid−liquid mushy zone, f is the volume fraction of liquid, δ is a relatively small number (0.001) to prevent division by zero; A_{mush} is the mushy zone constant, P_σ is the surface tension acting on liquid−vapor interface which has been transformed by CSF model (continuum surface force) into body force [21], P_{r} is the evaporation-induced recoil pressure, g is gravity, β is the thermal expansion coefficient, T_{ref} is the reference temperature, H is the enthalpy, c_p is the specific heat capacity, k_1 is the thermal conductivity, and q_{ebw} is the heat flux of electron beam. Specific expressions of surface tension and recoil pressure are as follows:

$$P_{\text{r}} = AB\exp\left(-\frac{\Delta_{\text{vap}}H_{\text{m}}}{RT}\right) \tag{4}$$

$$P_\sigma = \sigma\kappa = \sigma\left(-\nabla\cdot\frac{\boldsymbol{n}}{|\boldsymbol{n}|}\right) \tag{5}$$

where A is a coefficient related to the ambient pressure (0.55 for EBW atmosphere), B is a coefficient related to the material property, $\Delta_{\text{vap}}H_{\text{m}}$ is the latent heat of vaporization, R is mole gas constant, σ is surface tension coefficient, κ is the curvature of free surface, and $\boldsymbol{n}$ is the unit normal vector.

2.2 Tracking of keyhole

In this work, the VOF algorithm is used to track the dynamic profile of keyhole. The function $F(x, y, t)$ is